

Physics with the Main Injector

- The Machine
- The Physics
 - Neutrino Mixing/Mass
 - Kaon System
 - B system
 - Electroweak
 - Beyond the standard model
 - The Higgs
- The Program

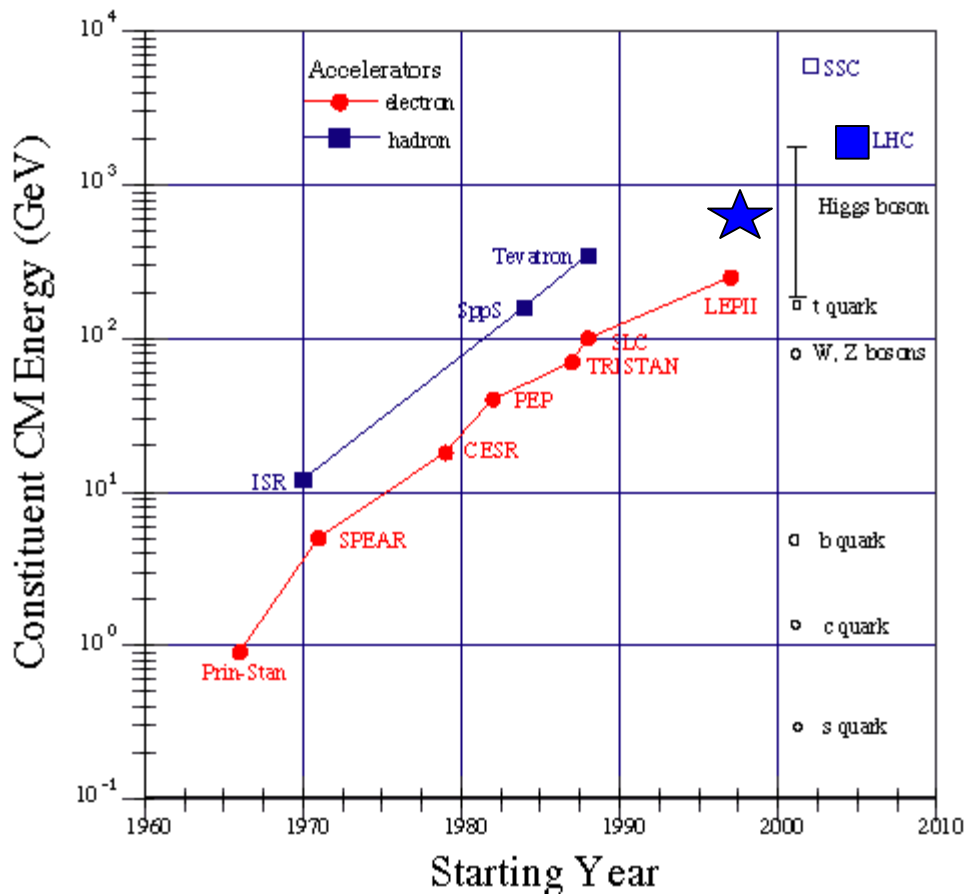
H. E. Montgomery,
DPF'99, UCLA, Jan. 8, 1999.

Acknowledgements

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- John Womersley
- U.T.Cobley et al

Livingston Plot

Progress in High Energy Physics
Depends on Advancing the
Energy Frontier



Increased Luminosity -->

Increased Constituent CM Energy

1800 --> 2000 GeV --> 40% for Top X sec

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Main Injector Performance

	Pbar Production	Fast Spill	Slow Spill
Energy(GeV)	120	120	120
Protons per cycle	$5.0 \cdot 10^{12}$	$3.0 \cdot 10^{13}$	$3.0 \cdot 10^{13}$
Flat Top (sec)	0.01	0.01	1.00
Cycle Time (sec)	1.47	1.87	2.87

Mixed Mode delivers $5.0 \cdot 10^{12}$ to pbar target
and $2.5 \cdot 10^{13}$ to experimental target every
1.87 or 2.87 seconds.

Proton Economics

Collider/NuMI Mode delivers $5.0 \cdot 10^{12}$ to pbar target and $2.5 \cdot 10^{13}$ to experimental target every 1.87 secs.

<5% impact on pbar production

Collider/Slow Spill Mode delivers $5.0 \cdot 10^{12}$ to pbar target and $2.5 \cdot 10^{13}$ to experimental target every 2.87 secs.

15-20 % impact on pbar production
stores will be longer, RECYCLER
helps.

Slip Stacking(x2),

Booster Aperture(x~1.5) =>

$5\text{-}10 \cdot 10^{13}$ protons ultimately.

Luminosity

**Protons in
Bunch**

**Total
Antiprotons**

Frequency

$$L = \frac{f N_p (B N_{\bar{p}})}{2\pi(\sigma_p^2 + \sigma_{\bar{p}}^2)} F(\sigma_z/\beta^*)$$

Beam Sizes

**Beam Shape Form factor
at Intersection**

Antiprotons

- Production

- 120 GeV Protons impact on target
- 8 GeV antiprotons produced, large angles
- focussed using Lithium Lens

- Accumulation

- antiprotons injected into large aperture accelerators
- Debuncher
- Accumulator
- Recycler

- Cooling

- multiple stochastic cooling systems
- different bandwidth systems react to different characteristics of the beam

- Acceleration

- Main Injector 8 to 150 GeV
- Tevatron 150 GeV - 1000 GeV

Antiprotons

- Recycling

- during store luminosity reduces
- main effect is dilution of bunches (as compared to pbar attrition due to collisions)
- at end of store, half of antiprotons remain

- **Reuse them!**

- Decelerate to 120 GeV
- extract from Tevatron into Main Injector
- decelerate to 8 GeV
- extract into Recycler Ring

- Recycler Ring

- Permanent Magnet Storage Ring
- Magnetic field controlled by mechanical construction of magnets
- Reliable, less dependent on power glitches!
- Also used for cooling antiprotons after production and Accumulator

Tevatron Collider Parameters

	Tevatron Run Ib	Tevatron Run II	Tev33
Bunch Spacing (nsec)	3500	396/132	132
Inst. Luminosity ($10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$)	1.6	5/20	50
Int. / Crossing	1-2	1-2/1-2	5
Luminous Region (cm)	30	30/15 (Xing Angle?)	30
Integrated Luminosity (fb^{-1})	0.1	2-4	10-30
			Luminosity Levelling

Tevatron Luminosity Evolution

Year	Peak Luminosity $10^{31} \text{ cm}^2 \text{ sec}^{-1}$	Integrated Luminosity fb^{-1}	Cumulative Luminosity fb^{-1}
2000	5	0.5	0.5
2001	10	1.0	1.5
2002	20	2.0	3.5
2003	Shutdown		
2004	40	4.5	8.0
2005	50	5.5	13.5
2006	50	5.5	19.0
2007	50	5.5	24.0

Main Injector Status

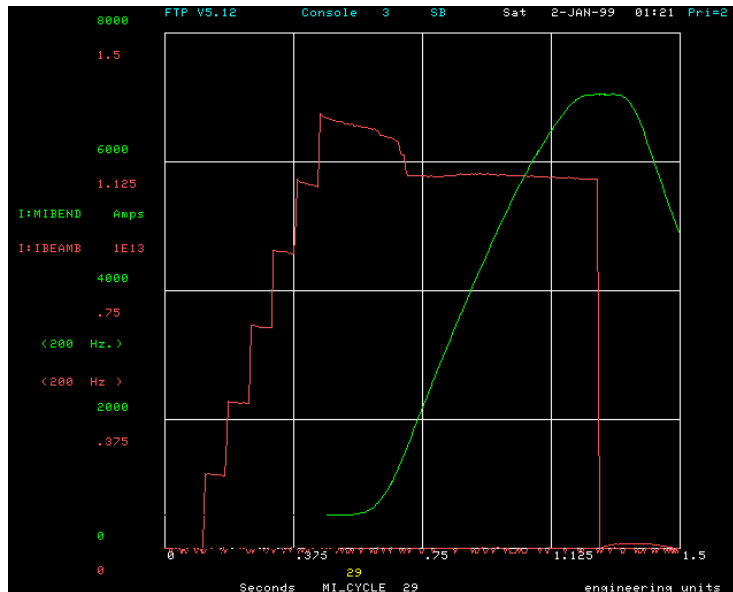
- **Civil Construction Complete except**
 - **Recycler Stochastic Cooling link.**
- **Installation Complete except**
 - **Recycler Magnets (95% complete)**
 - **Recycler Vacuum(65% under vacuum)**
 - **Main Injector-Recycler Injection Line**

All Complete February

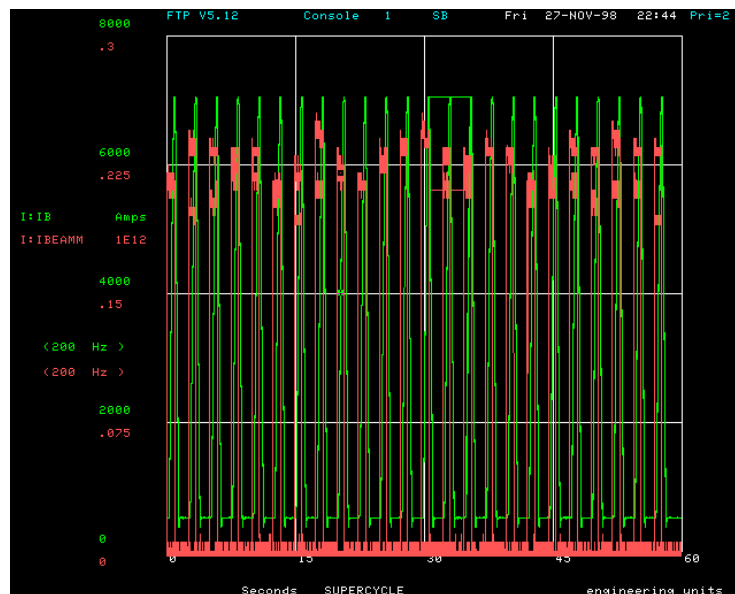
 - **Recycler Stochastic Cooling**
- **Commissioning**
 - **Beam Accelerated to 150 GeV
(Injection Energy to Tevatron)**
 - **Beam Accelerated to 120 GeV**
 - **95% Efficiency**
 - **2.5 sec cycle time**
 - **$1.0 \cdot 10^{13}$ protons per cycle**
- **MI operating near design params.**

Main Injector Status

- $1 \cdot 10^{13}$ protons/cycle



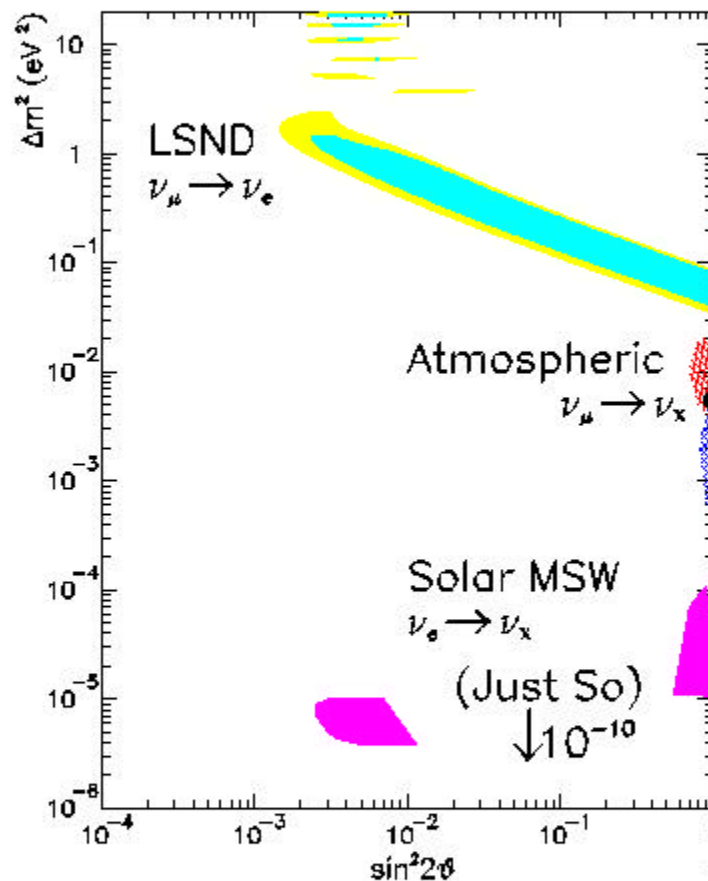
- 2.5 sec cycle time



Neutrinos: Status

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

So far... 3 indications



- Are all hints *really* oscillations?
- For each case, what's the Δm²?

NuMI/MINOS

- **Targets the “Atmospheric” Indications**

Relatively low Δm^2

Relatively High Energy

Relatively Long Baseline

- **Seeks $\mathbf{n}_m \rightarrow \mathbf{n}_t$**

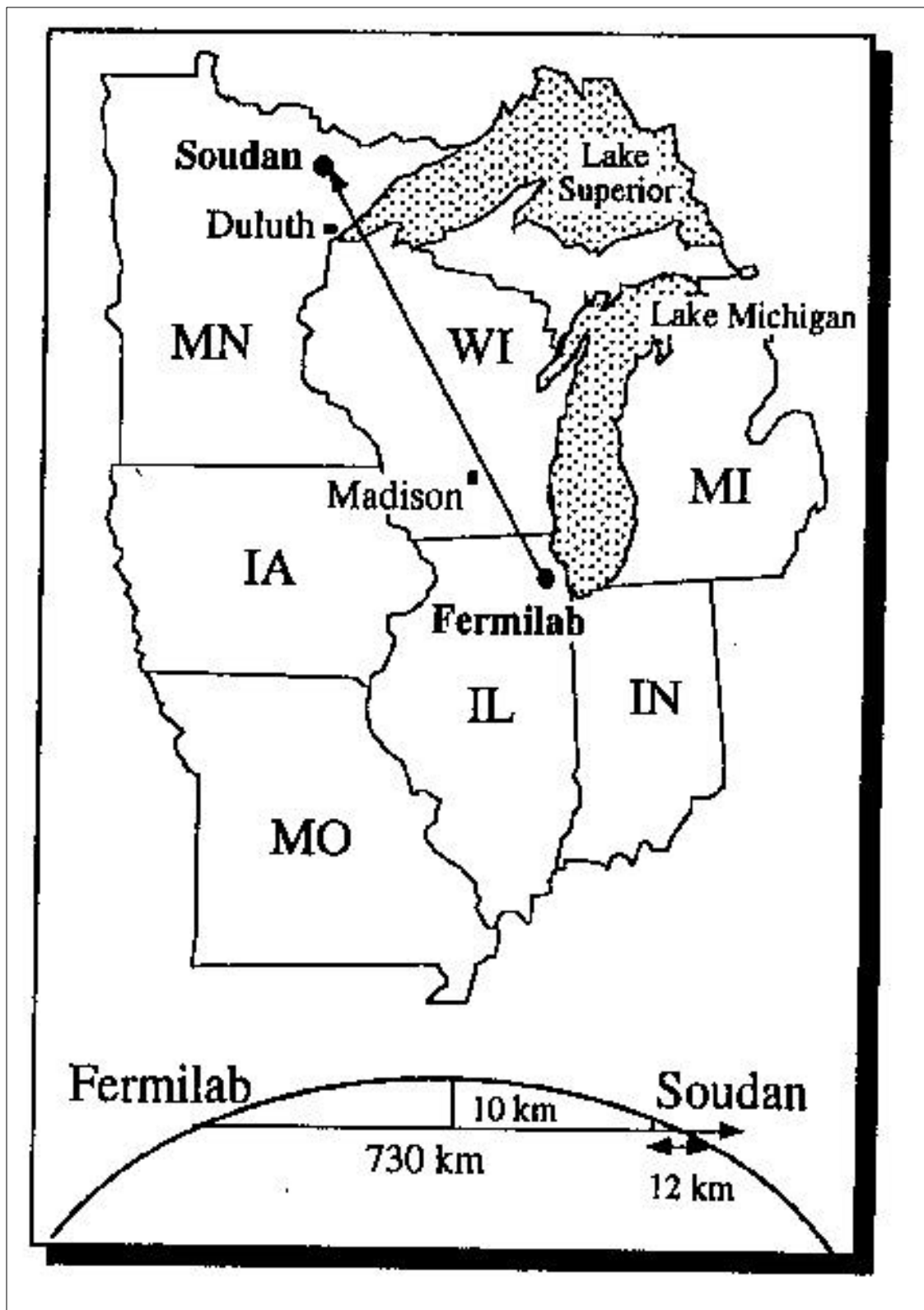
Disappearance, Appearance

Distinguishes sterile

- **Two Detectors**

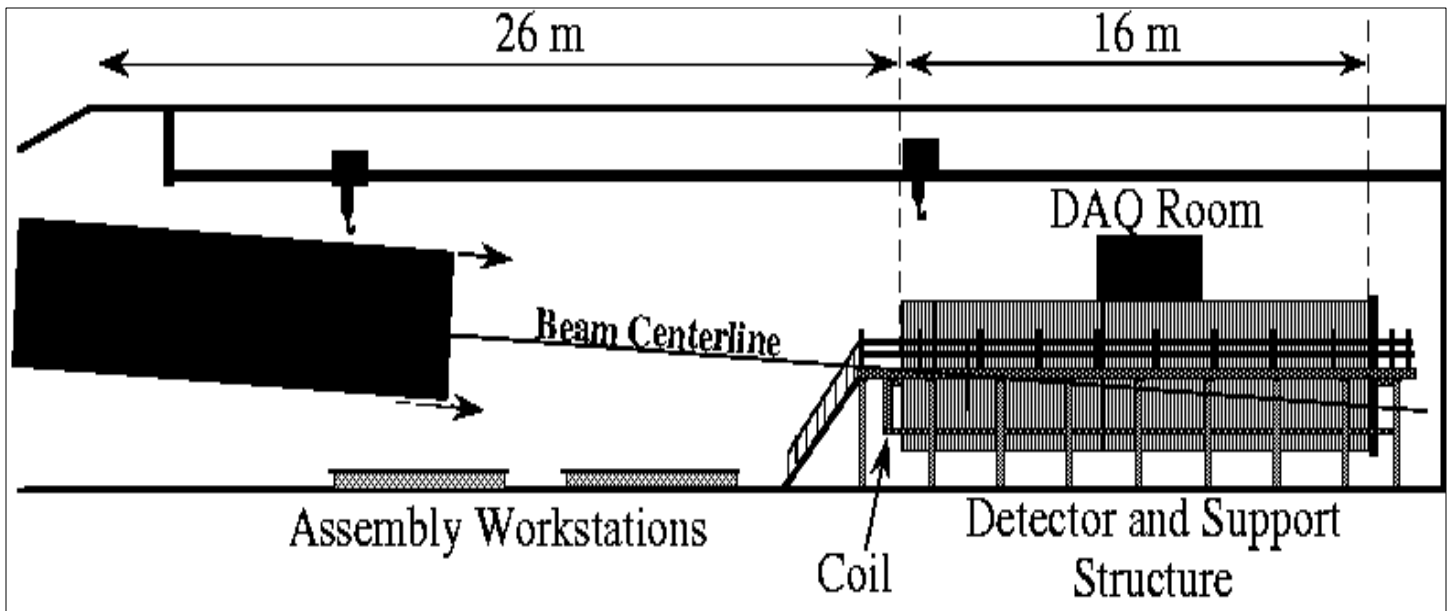
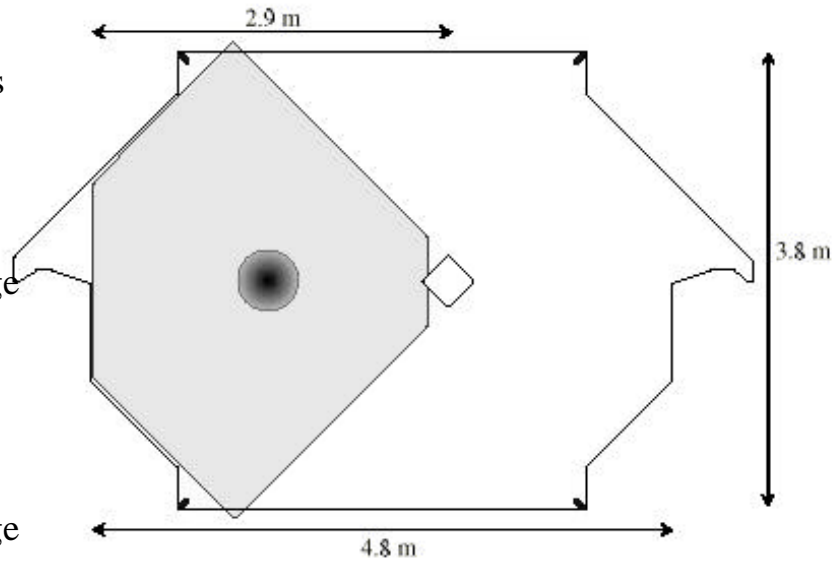
- **Main Injector to Minnesota ,
(Soudan Mine)**

NuMI/MINOS



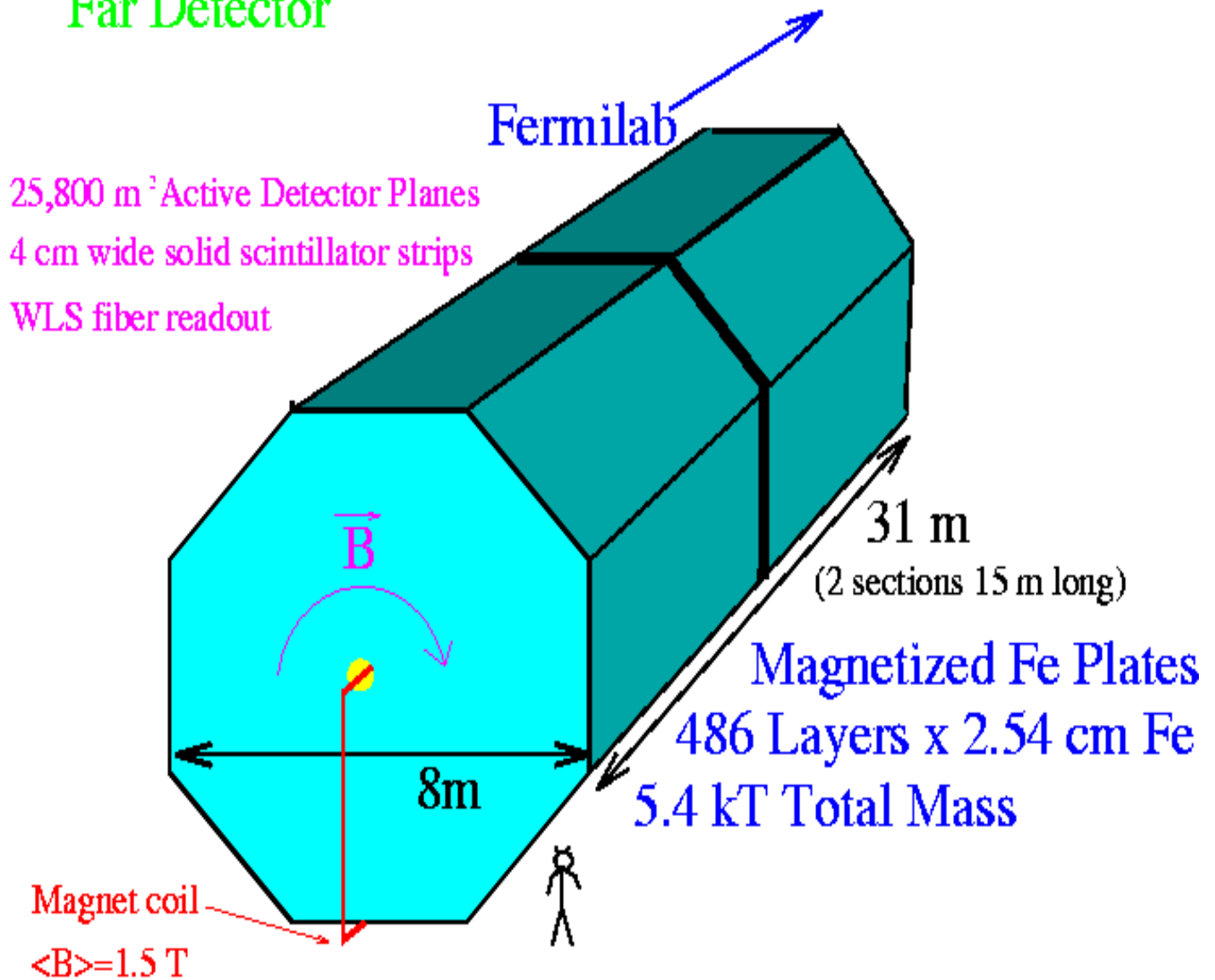
Minos Near Detector

- 16.6 m long, 980 tons
- 280 “squashed octagon” planes
- **Forward section:** 120 planes
 - 4/5 partially instrumented
 - 1/5 planes: full area coverage
- **Spectrometer section:** 160 planes
 - 3/4 planes not instrumented
 - 1/4 planes: full area coverage



MINOS Far Detector

Far Detector



MINOS Physics Goals

- Obtaining firm evidence for oscillations:

- CC interaction rate
- CC energy distribution
- NC/CC rate ratio
- NC energy distribution

These are statistical measurements, mode independent, capable of being done with the baseline detector configuration. In addition:

- Atmospheric neutrino measurements

- Measurement of oscillation parameters,

Δm^2 , $\sin^2 2\theta$

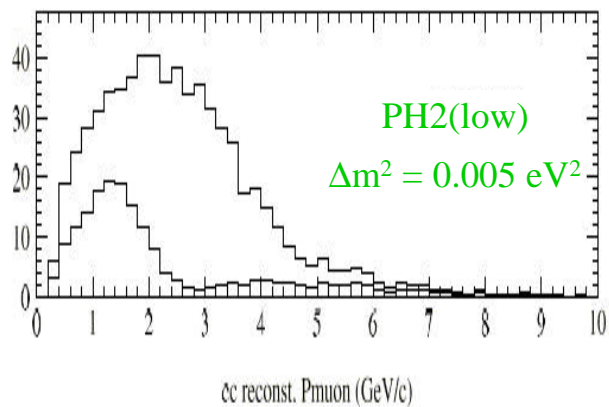
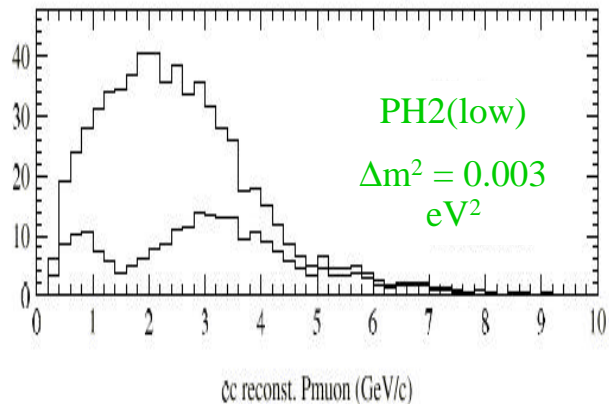
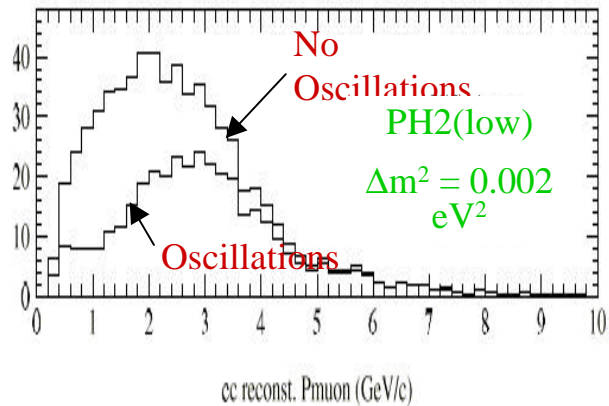
- CC energy distribution [statistical, with baseline detector configuration, oscillation mode independent]
- Rate and energy distribution measurements with narrow band beam running [requires NBB configuration]
- Observation of τ production [measures product $(\Delta m^2)^2 \times \sin^2 2\theta$ and is best done in the hybrid emulsion detector upgrade]

MINOS Physics Goals

- Determination of the oscillation mode(s)
 - Statistical measurements with the baseline detector
 - NC/CC rate measurements
 - Identification of ν_e by topological criteria
 - Identification of ν_τ by its exclusive decay modes (works best if Δm^2 is relatively high; some modes require NBB configuration)
 - Observation of appearance of ν_τ and/or ν_e in the hybrid emulsion detector (not part of baseline)
 - Observation of τ production and subsequent decay, identified by a kink close to the vertex (ν_τ)
 - Observation of electron originating at the production vertex (ν_e)
- MINOS experiment will be able to perform these measurements over the full allowed range of parameter space

Oscillation Parameter Measurement

- CC event energy test
- Select CC events (length)
- Calculate event energy (muon + EM + hadron)
- Shape difference indicates oscillations
- Dip position gives Δm^2
- Dip depth gives $\sin^2(2\theta)$
- Simulation includes detector energy resolution



MINOS Energy Spectra

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10 kt-yr
Exposure

Solid lines - energy
spectrum without
oscillations

Dashed histogram -
spectrum in presence
of oscillations

MINOS Sensitivity, High Energy

$$\nu_{\mu} \rightarrow \nu_{\tau}$$

$$\nu_{\mu} \rightarrow \nu_e$$

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A - Disappearance

B - NC/CC rate test

C - CC-event energy test

A - Electron appearance

B - NC/CC rate test

C - Disappearance

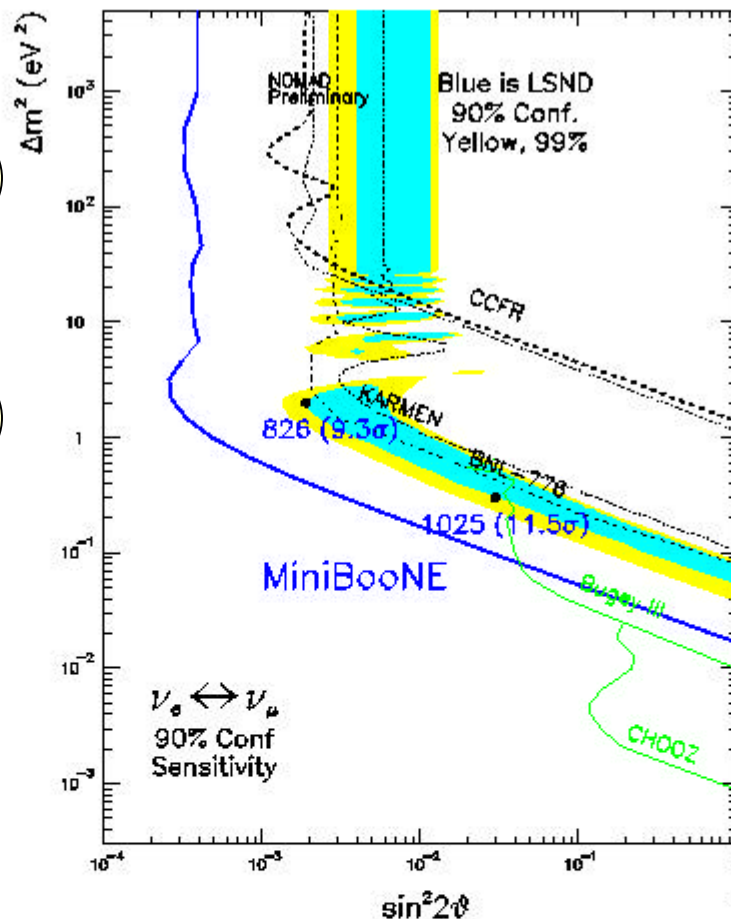
BooNe

BooNE: The Booster Neutrino Experiment at Fermilab

n_e Appearance

n_m Disappearance

500 meters,
0.1 - 1.0 GeV



A 2-phase experiment:

Phase 1: “*MiniBooNE*” (one detector) – 2001

- Disprove or Demonstrate LSND signal at $\geq 5\sigma$ ($\geq 10\sigma$ if E -dependence is used)

Phase 2: “*BooNE*” (two detectors) – 2003

- Measure oscillation parameters if signal is observed.

Quarks: Flavor

CKM Matrix of Flavors: u,d,c,s,t,b

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

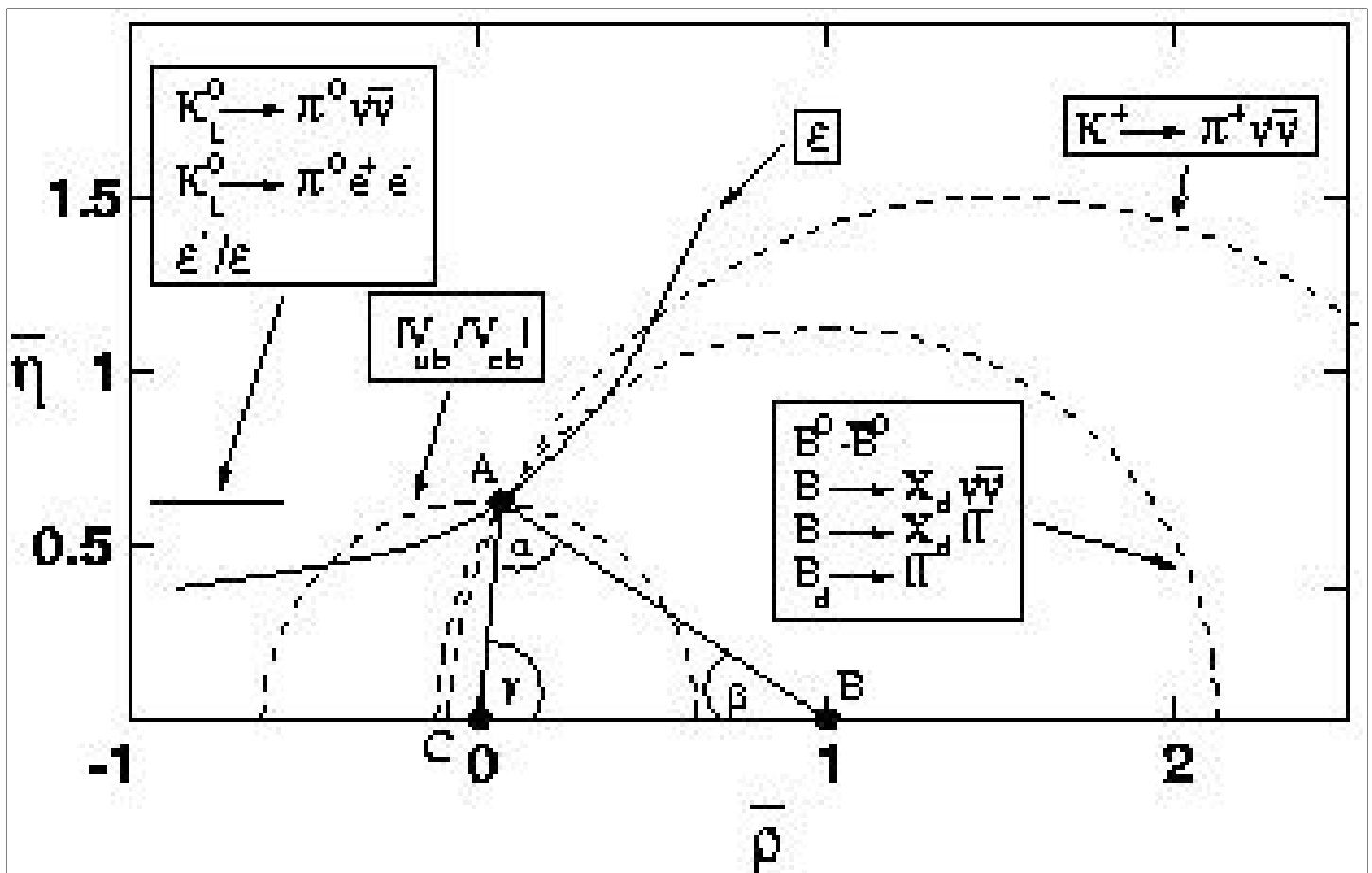
Wolfenstein Representation

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2-i\eta & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Different Processes give different elements

CKM Triangle

Triangle from Unitarity



Perfect Measurements

Kaons: Status

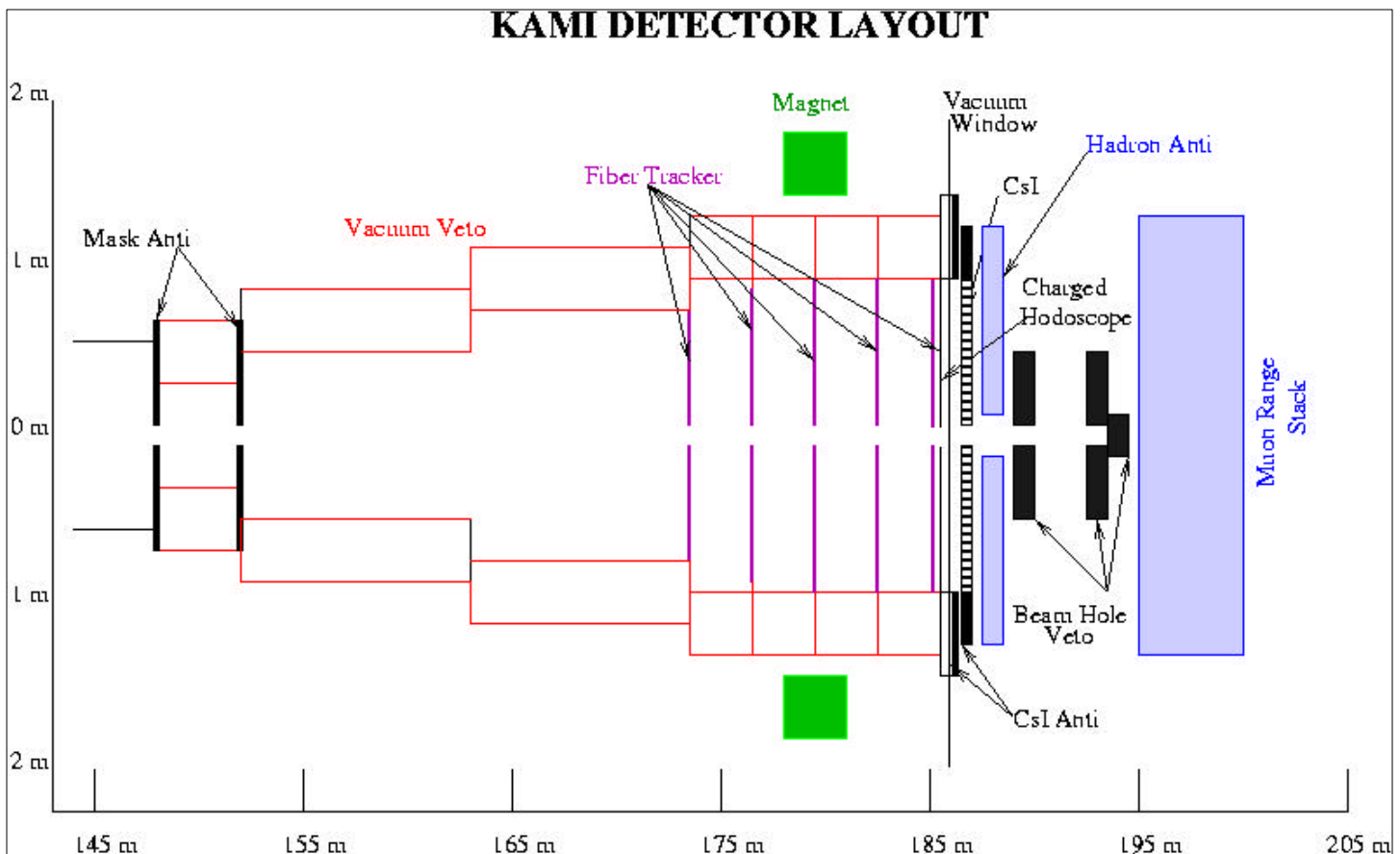
- Kaon System is the only one in which CP Violation is observed.
- Only observed in K_L^0 !
- Is CP viol. Indirect, in the Mixing?
- Is CP viol. Direct, in the Decays?
- Try to Measure ϵ' . E731, NA31,
Uncertainty $1 \cdot 10^{-4}$ KTeV, NA48, KLOE

Close to Zero!

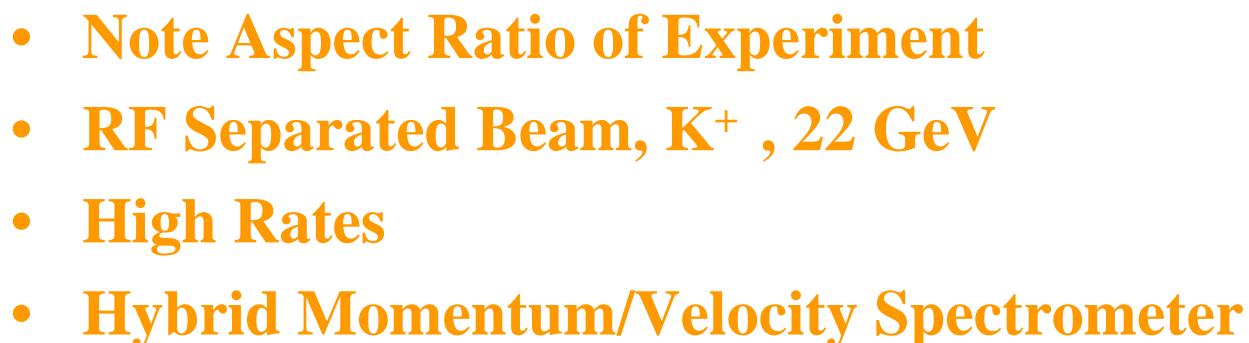
“KAMI” Experiment

Proposed

$$K_L^0 \Rightarrow \pi^0 \nu \nu$$



- **Note Aspect Ratio of Experiment**
- **Critical Elements,**
Calorimeter, Vacuum γ Vetos
Beam Hole veto
- **Fiber Tracker for Charged modes**

$$\mathbf{K}^+ \Rightarrow \pi^+ \nu \nu$$


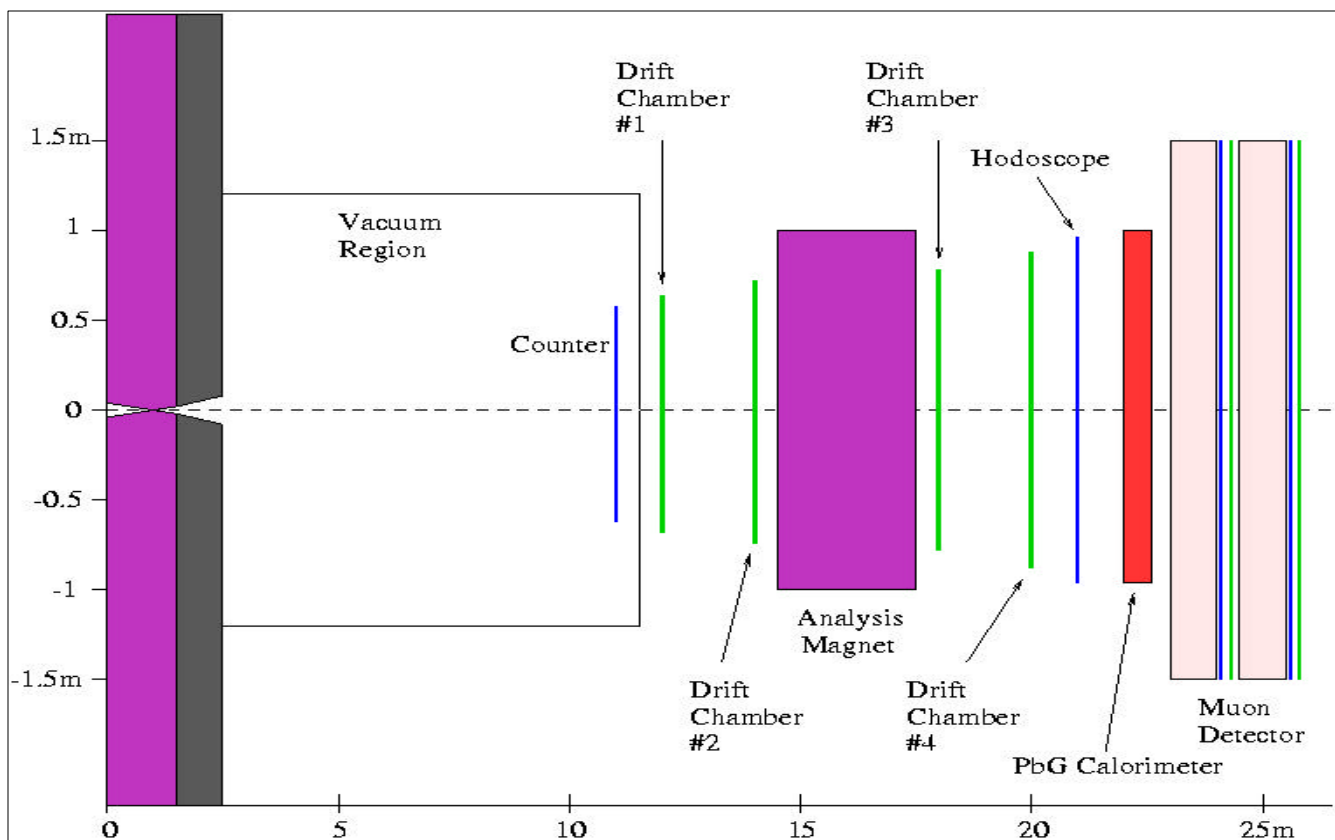
“CPT” Experiment

Proposed

K^0 η_{+-} phase CPT Test at Planck Scale

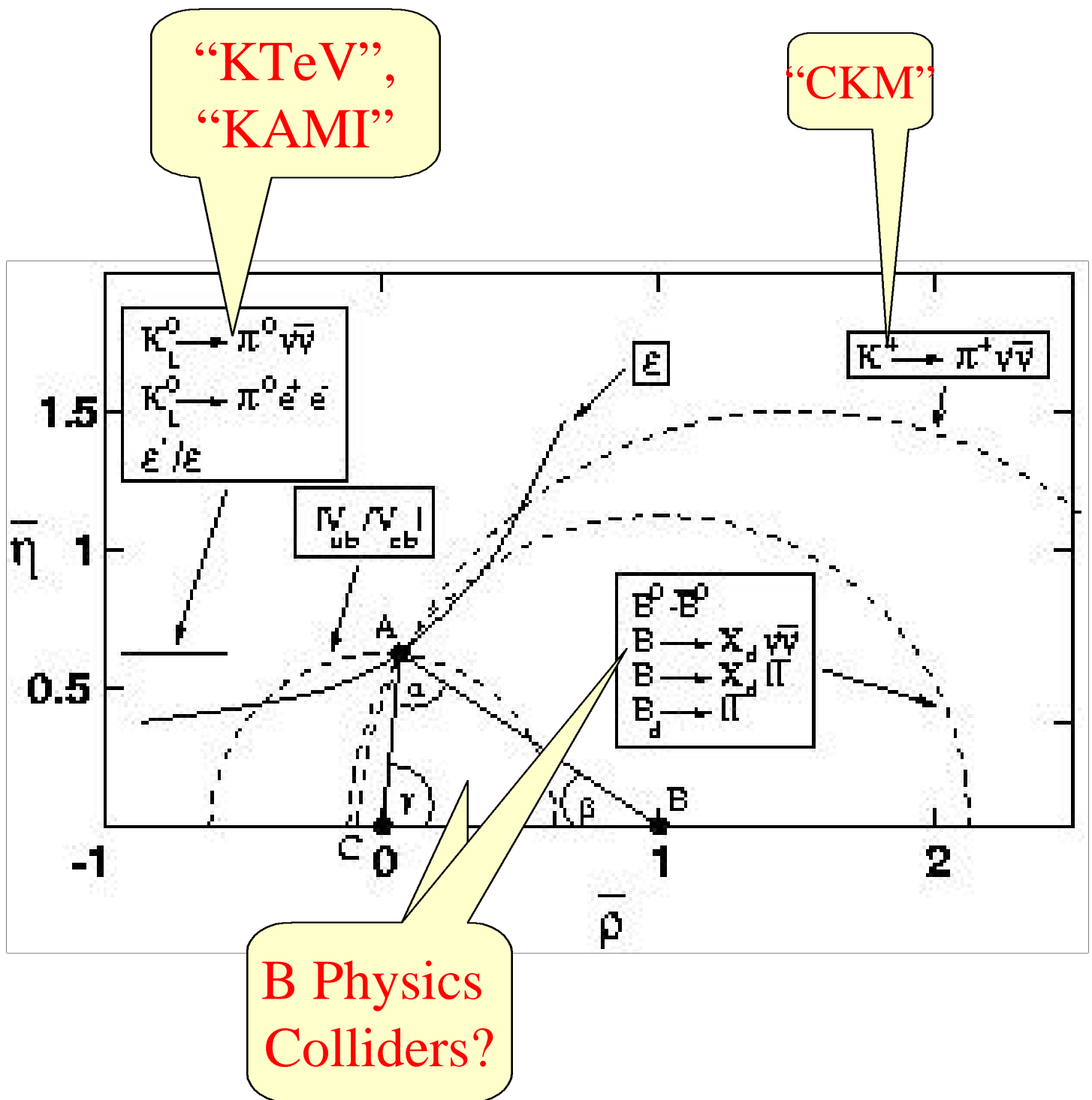
$K^0_{L,S}$ CP Violation : $\pi^+ \pi^- e e$, $\pi^0 e e$

K^0_L : $\pi^0 \gamma \gamma$



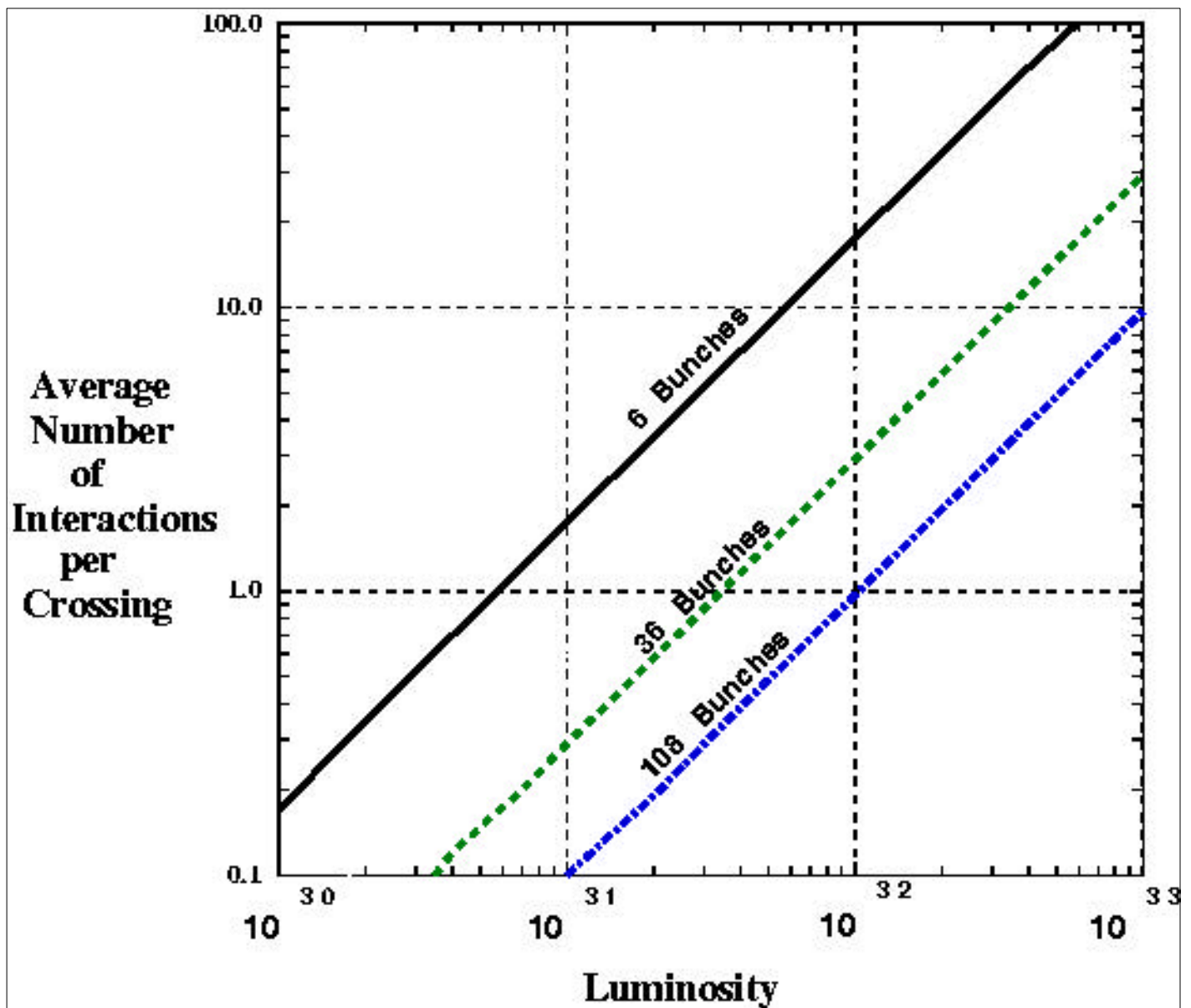
- **Short Experiment: maximise $K^0_{L,S}$ Interference**
- **K^0 Beam from RF Separated K^+ Beam, 22 GeV**

FNAL Kaon Measurements



FNAL B Measurements

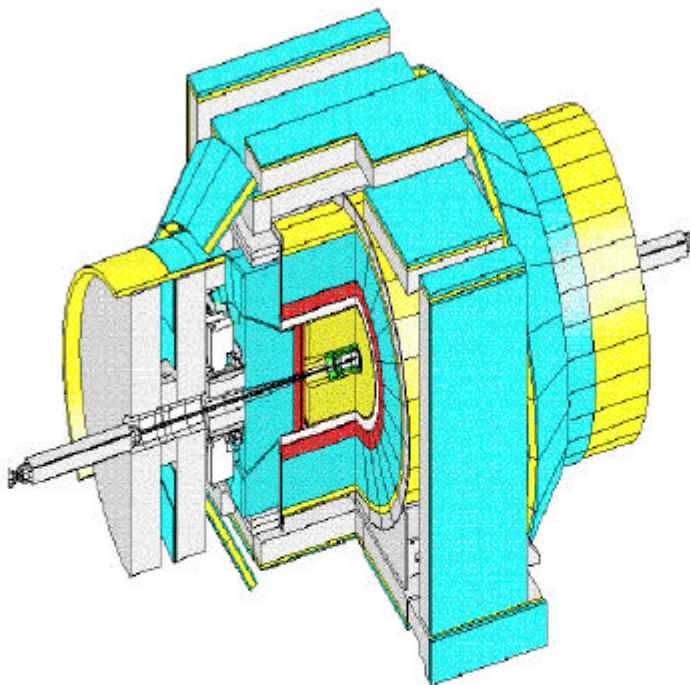
Interactions per Crossing: Tevatron Collider



The CDFII Detector

RETAINED FROM CDFI

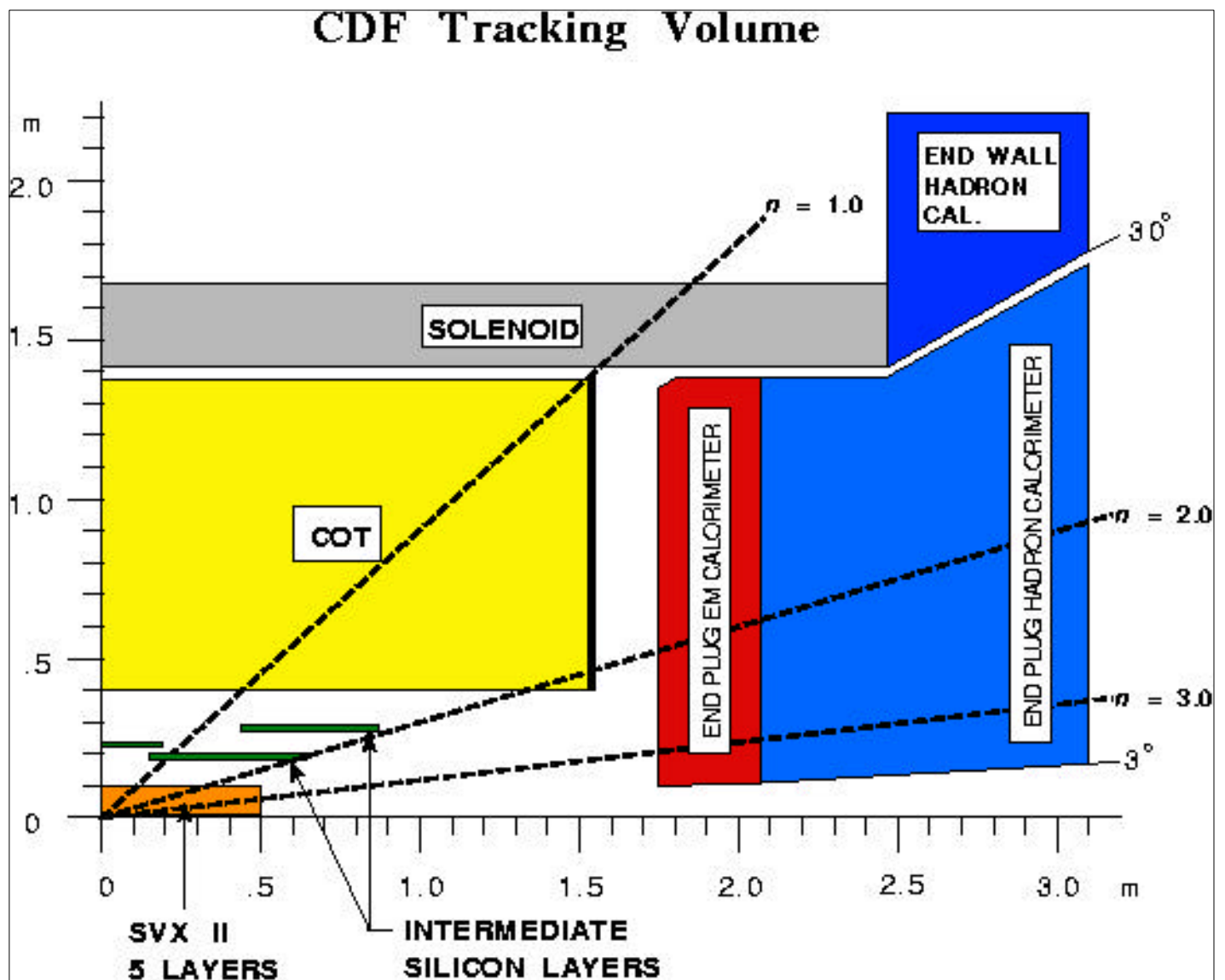
- Solenoidal magnet
- Central and wall calorimeters
- Central and extension muon detectors



NEW FOR CDFII

- Tracking system
 - Silicon vertex detector (SVXII)
 - Intermediate silicon layers (ISL)
 - Central outer tracker (COT)
- Scintillating tile end plug calorimeter
- Intermediate muon detectors
- Front-end electronics (132 ns)
- Trigger system (pipelined)
- DAQ system (L1, L2, L3)

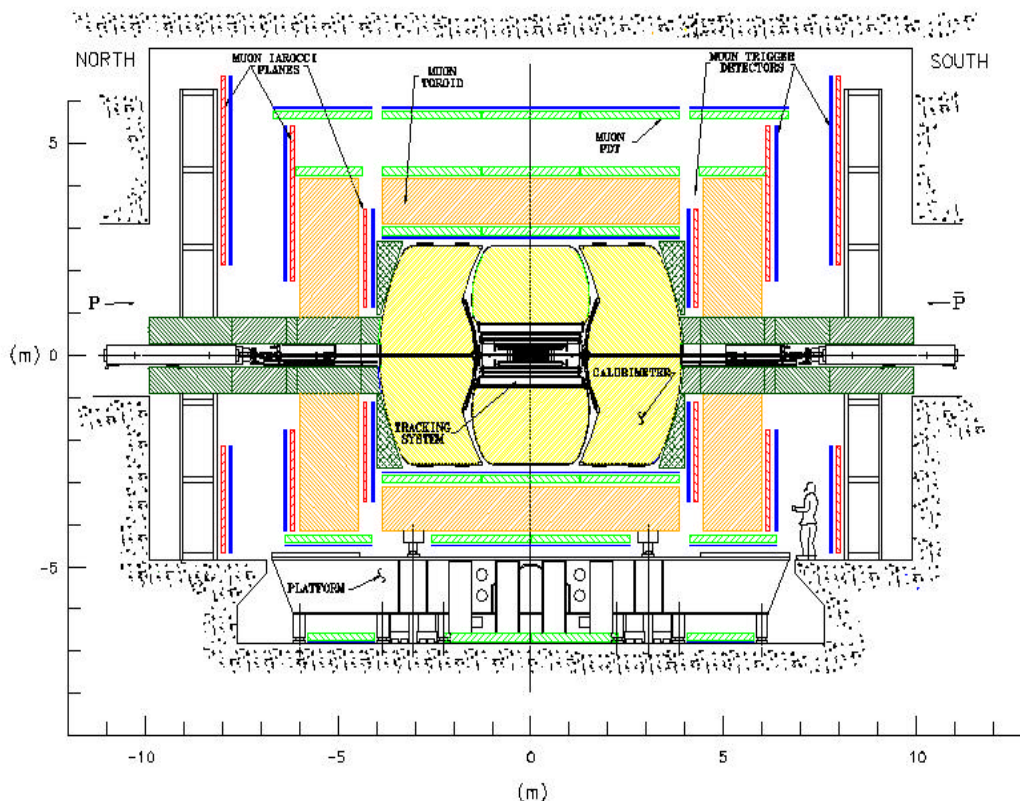
CDF Tracking



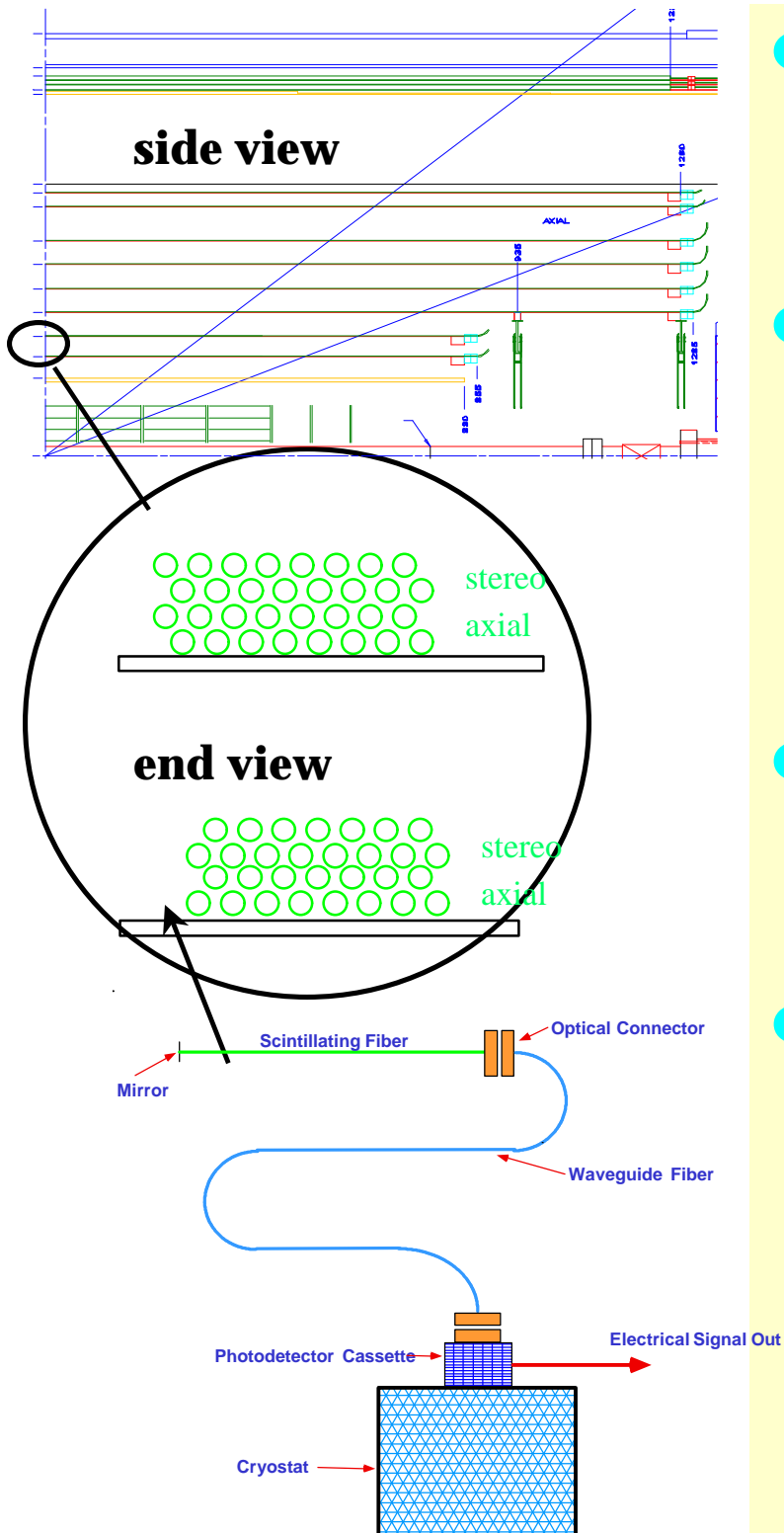
D0 Detector

New for Run II

- Solenoidal magnet
- Tracking, Fibers, Silicon
- Forward Muons
- Preshowers
- FE Elect., DAQ



D0 Fiber Tracker



● Barrels

- 8 carbon fiber barrels
- $20 < r < 50 \text{ cm}$
- full coverage to $\eta = 1.7$

● Scint Fibers

- $830 \mu\text{m}$ \varnothing , multiclاد
- 2.6m active length
- 10m clear waveguide to photodetector
- rad hard (100 krad)
(10yr @ 20cm @ 10^{32})

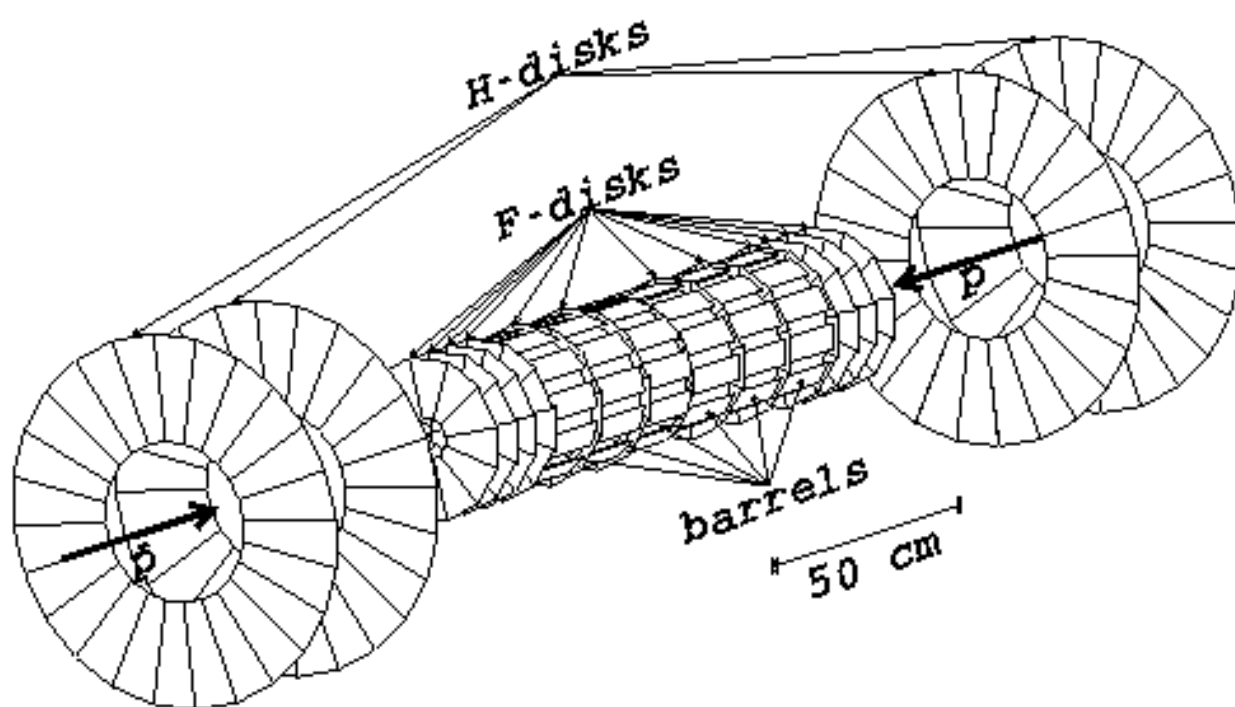
● Fiber Ribbons

- 8 axial doublets
- 8 stereo doublets (2° pitch)

● Readout

- 77,000 channels
- VLPC readout
- run at low temp (9 K)
- fast pickoff for trigger
- SVXII readout

D0 Silicon Microstrip Tracker



B Production Features

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η_B

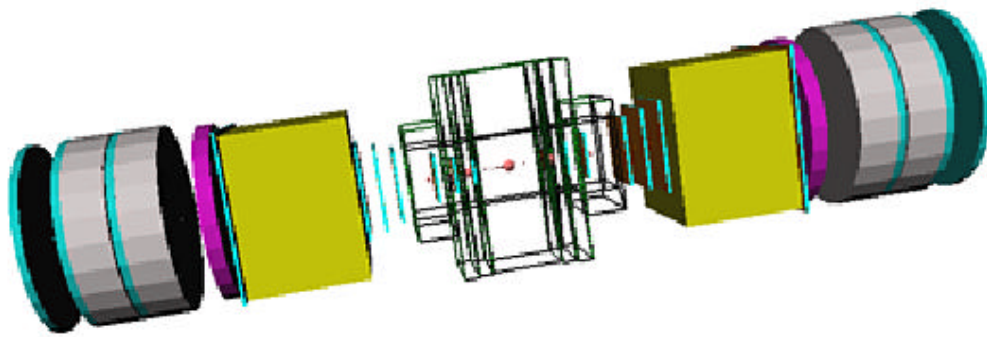
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$\beta\gamma$

η_B

BTeV Experiment

BTeV

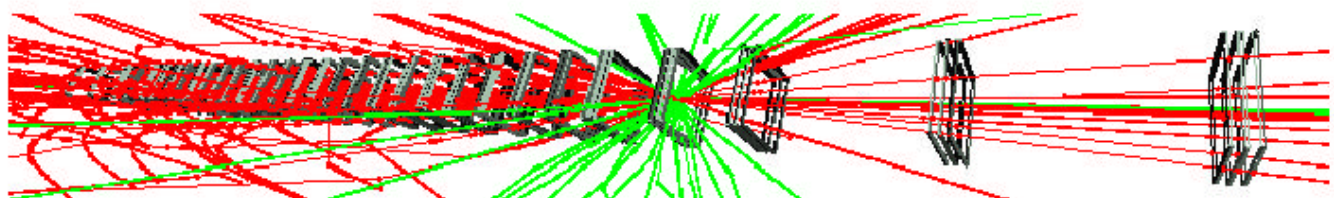


Pixel Detector with 31 yxy Stations inside beam vacuum
Dipole Magnet Steel Field Integral: 2.6T – m Vertical Bend
Indicators of field direction

Wire Chambers with Aperature $\tan \theta = 0.3$

Rich (C_4F_{10}/C_5F_{12}) Meaningful K/ π separation for
 $3.0 < p < 70 \text{ GeV}/c$. Optional areogel preradiator not shown

EM Calorimeter: Options Pb–Scint, Pb–liq. Ar, liq Kr, CsI
 μ absorber and Toroid μ trigger

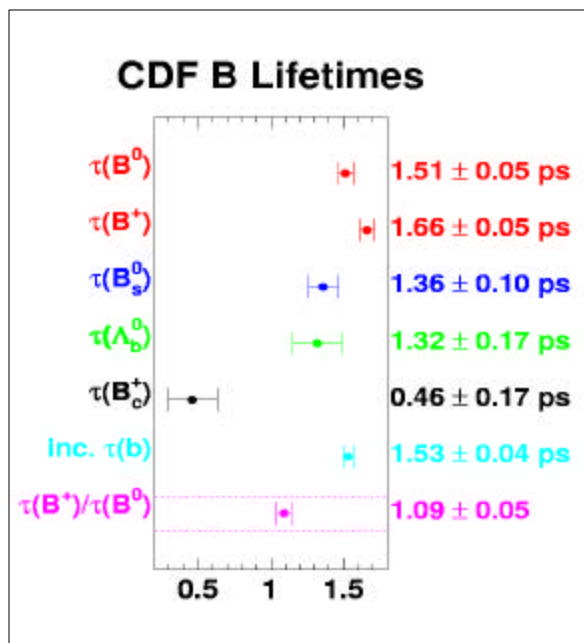
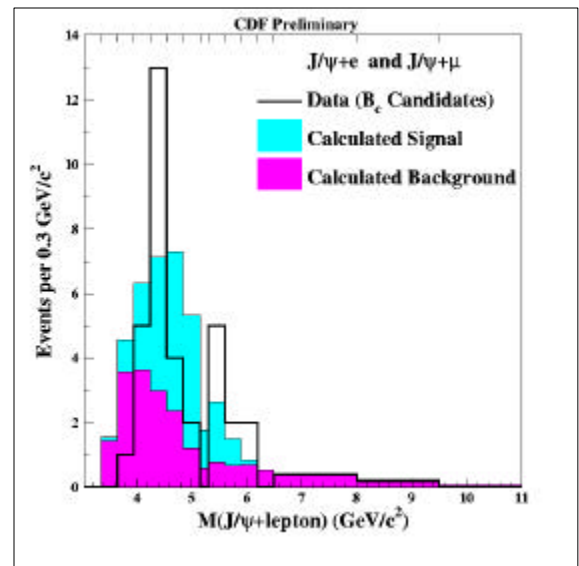


B Physics: Status

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- **B Cross Section**

- **B_c Observation**



- **B Lifetimes**
- **Note higher mass states B_s , Λ_b**

- **B Physics at Hadron Collider Established**

B Physics Measurements

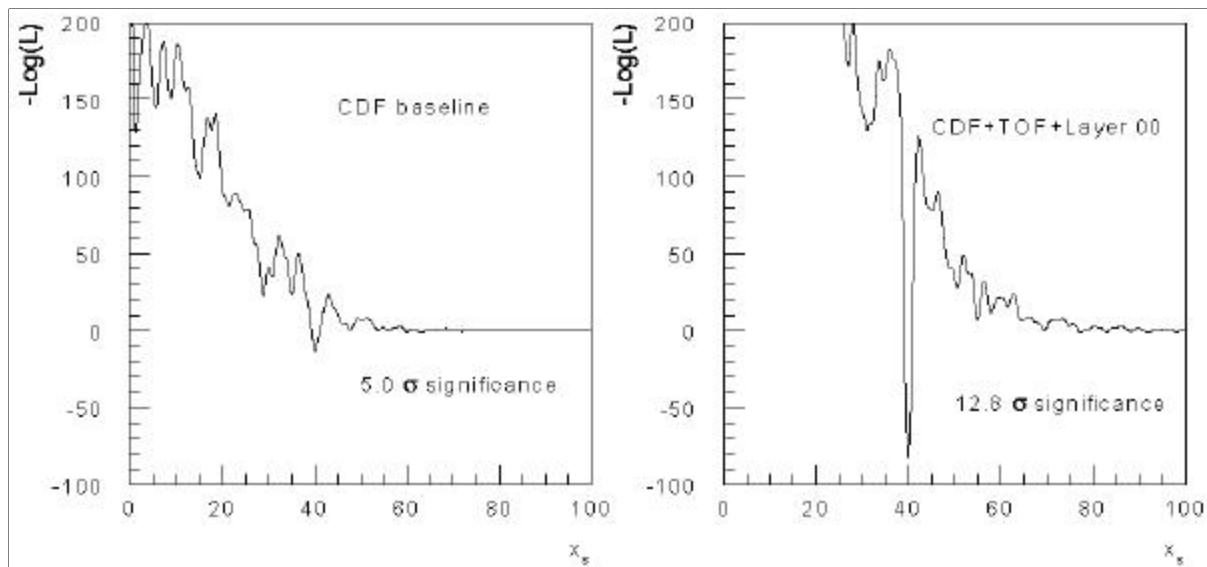
- $\sin 2\beta$

Run I $\Delta \sin 2\beta = 1.8 \pm 1.1 \text{ (stat)} \pm 0.3 \text{ (syst)}$

Only “Same-side” Tagging, will improve

Run II.. Expect $\Delta \sin 2\beta < 0.1$

- B_s Mixing 20,000 B_s with SVT trigger

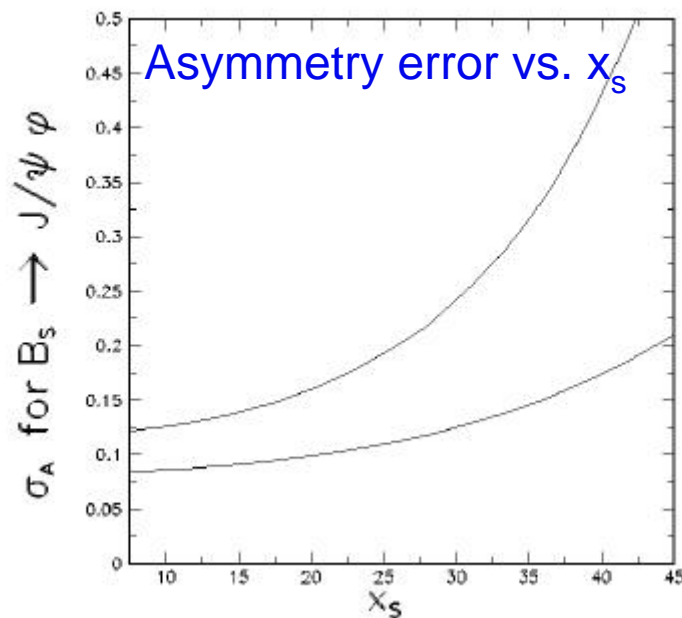


x_s Reach 40 - 60

B Physics Measurements

- **CP Violation in B_s**

- $B_s \rightarrow J/\psi \phi$



- **$\sin 2\alpha$, $\sin 2\gamma$**

- (tough, need rate, id, space resolution)

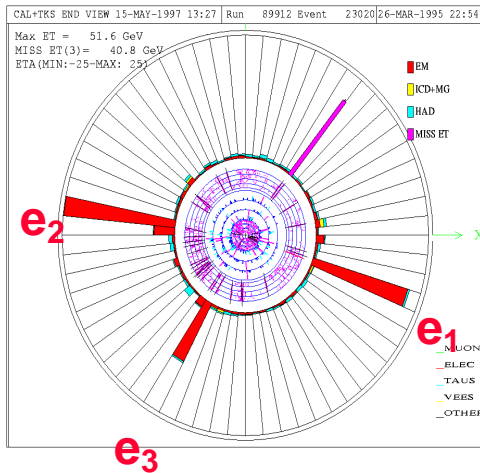
- **Rare Decays**

A Rich and Extensive Program

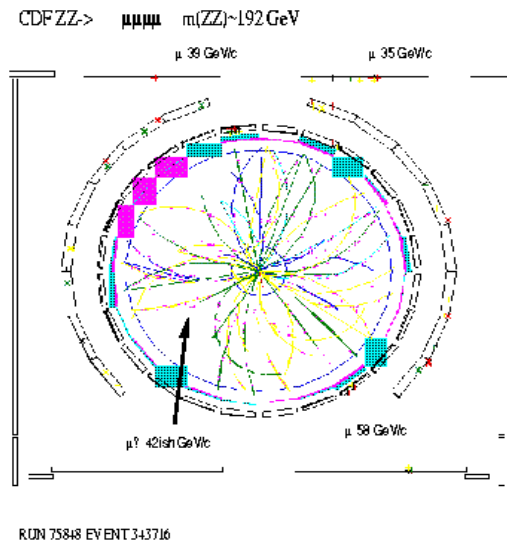
in good part beyond the B Factory reach

Electroweak Boson Couplings

WZ from D0



ZZ event CDF



Quantitative Expectations

- Factor of 20X in luminosity provides $\sim 2.5X$ improvement in T.G.C. limit. (at fixed form factor scale).
- Numbers of events (CDF + D0) estimate.

$W\gamma \rightarrow l\nu\gamma \quad \sim 3000$

$Z\gamma \rightarrow ee(\mu\mu)\gamma \quad \sim 700$

$WW \rightarrow ll\nu\nu \quad \sim 100$

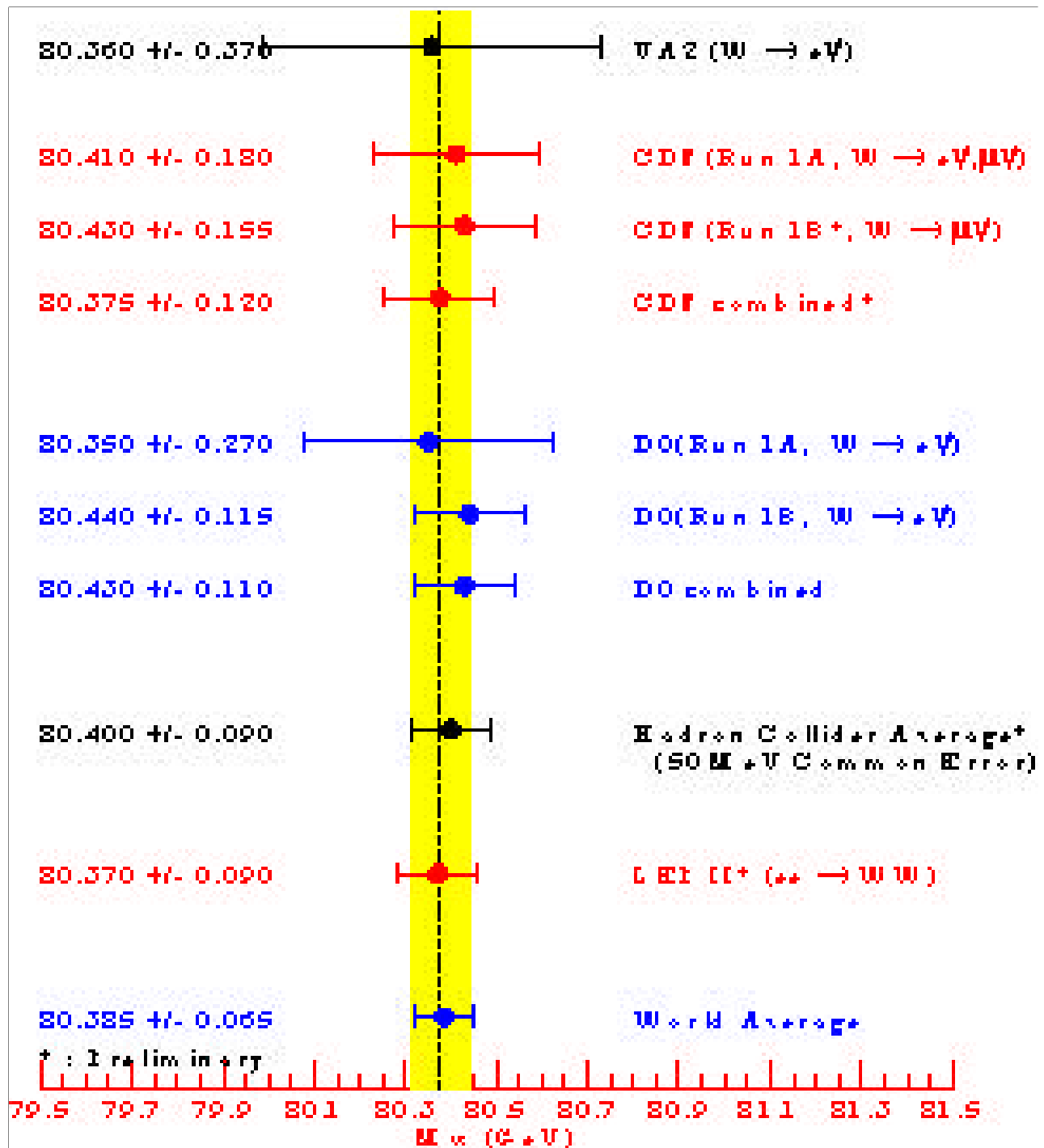
$WZ \rightarrow ll\nu \quad \sim 30$

$ZZ \rightarrow e's \text{ and } \mu's \quad \text{a few}$

Qualitative Expectations

- Wg and WZ radiation zero.
- Probe theoretical expectations for T.G.C.'s.

W-Boson Mass

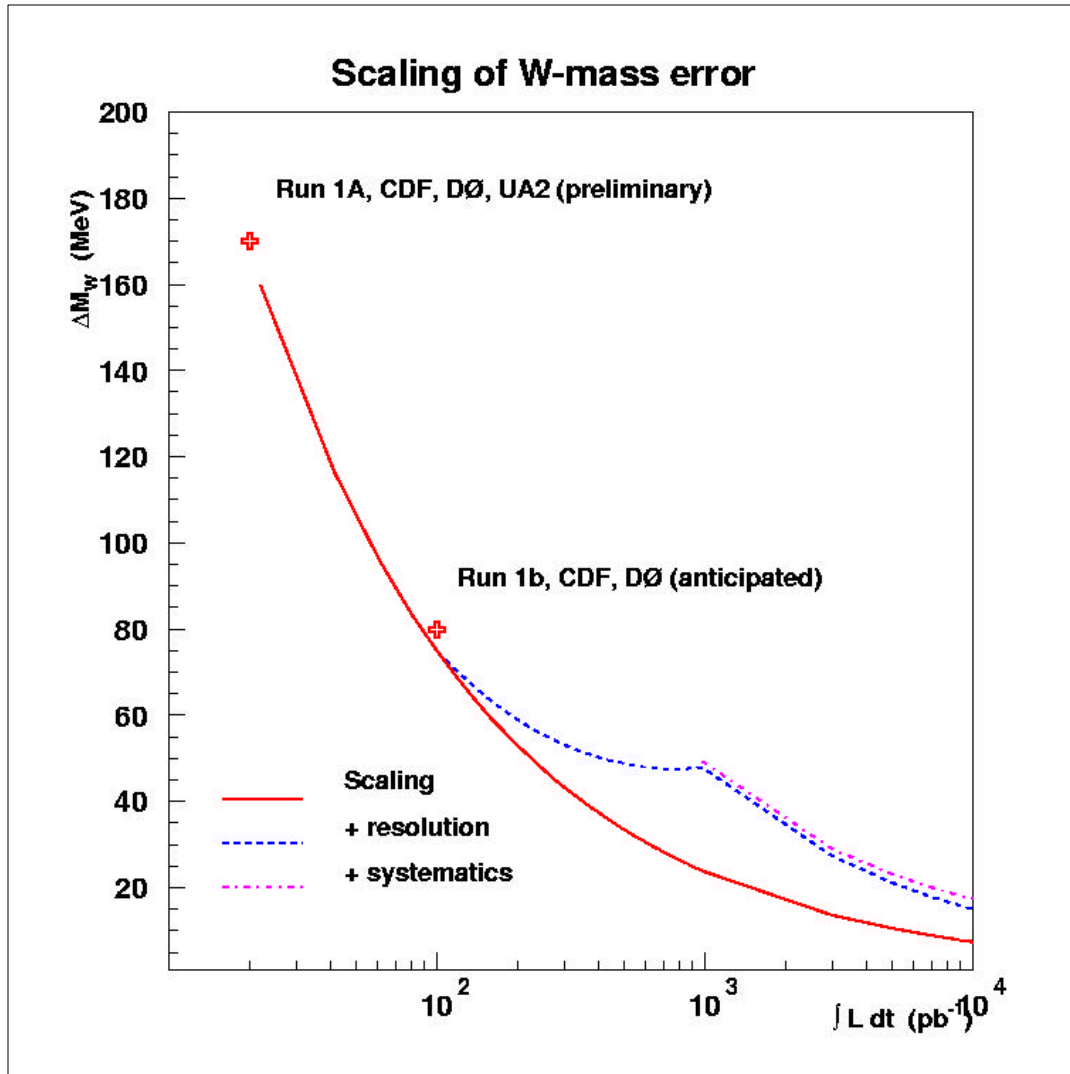


W mass Errors

	CDF	DO	
Statistical	100	70	} 95 (stat)
Momentum/Energy Scale	40	65	
Calorimeter Linearity	—	20	
Lepton Resolution	25	20	
Recoil Modeling	90	40	
Input $p_T(W)$ and PDF's	50	25	
Radiative Decays	20	15	
Higher Order Corrections	20	—	
Backgrounds	25	10	
Lepton Angle Calibration	—	30	
Fitting	10	—	
Miscellaneous	20	15	
Systematics	115	70	
Total (MeV)	155	120	

Run Ib Measurements

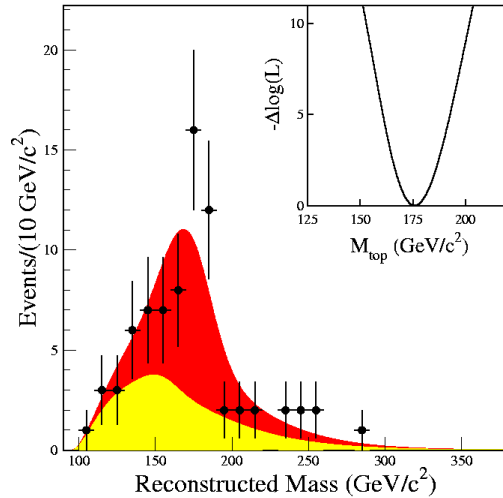
W-Boson Mass



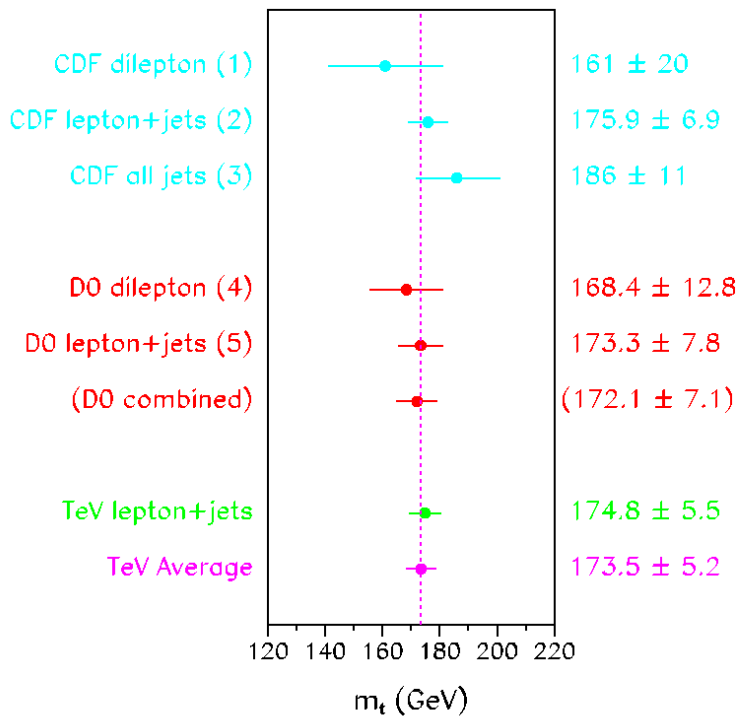
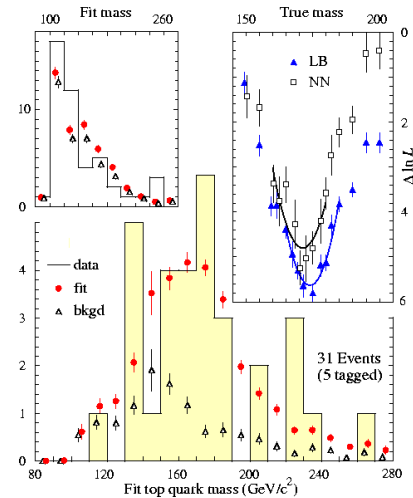
- Lots of Systematic errors are dependent on data, for example Z calibrations, and hence scale as data.
- Underlying events/pile up affected by “per-bunch” luminosity so reduced by having 100 bunches(132 nsec spacing)

Top Quark Mass

CDF(l+jets)

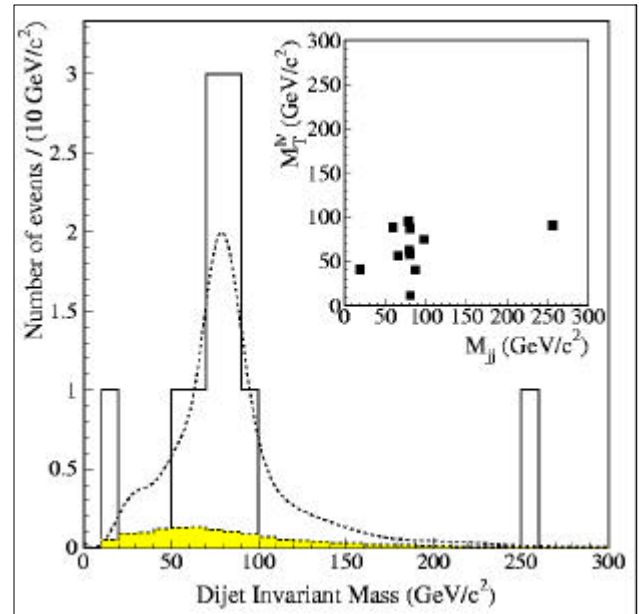
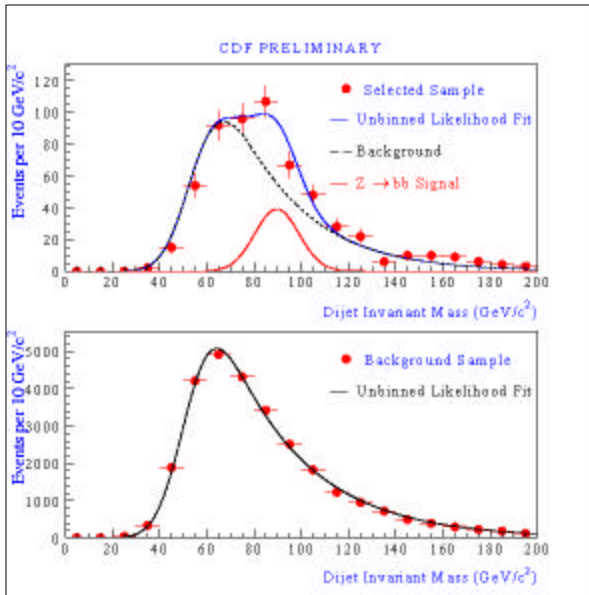


D0 (l+jets)



m_{top} [Gev/c²]
173.84^{+5.04}
 Tevatron Average

Top Quark Mass

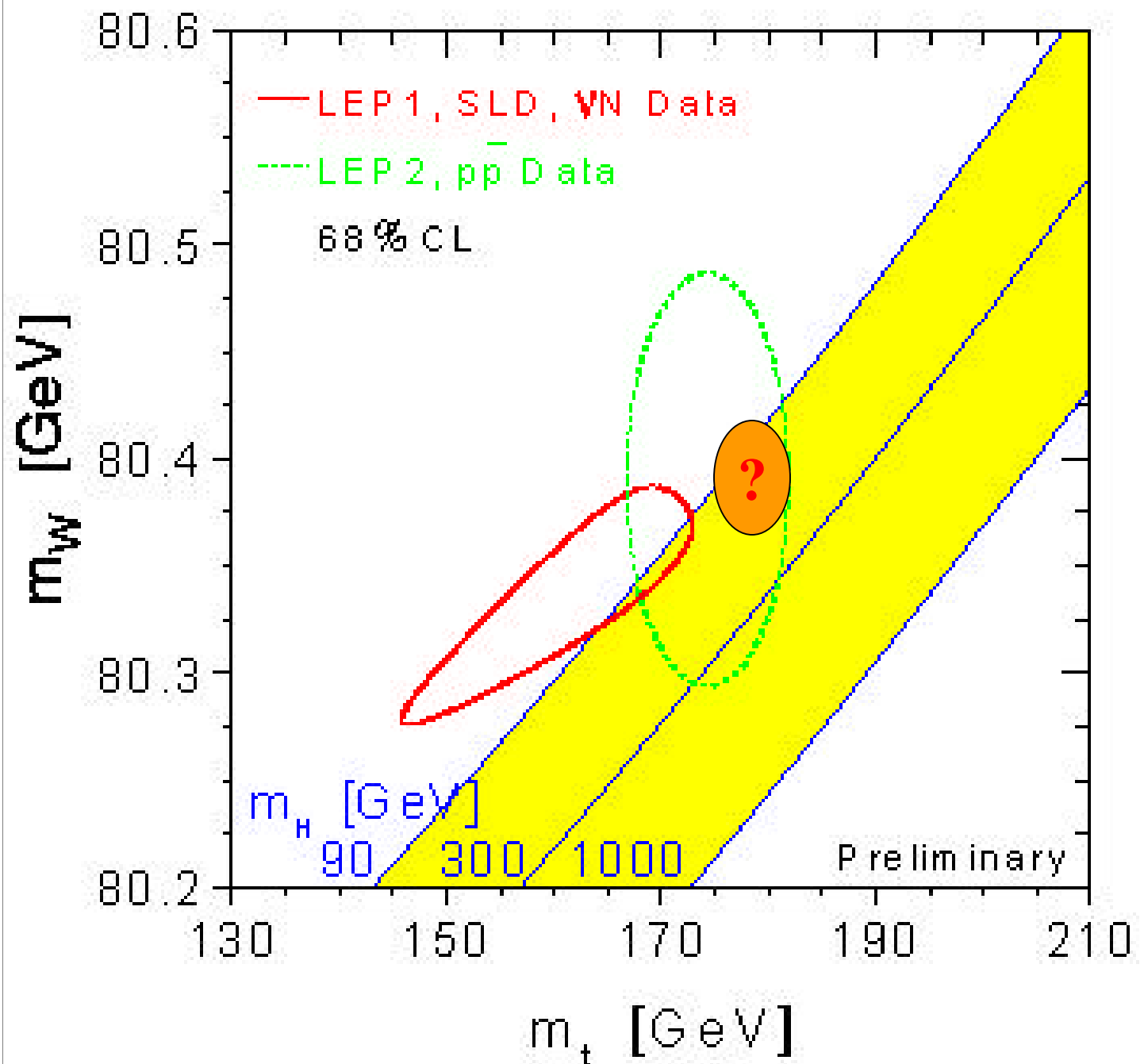


Single experiment, l + jets

UNCERTAINTY (GEV)	RUN I	RUN II
Statistical	5.6	1.3
Jet Energy Calib.	4.0	0.4
Gluon ISR/FSR	3.1	0.7
Detector Noise etc	1.6	0.4
Fit Procedure	1.3	0.3
All Systematic	5.5	0.9
Total	7.8	1.6

Other top quark physics, V_{tb} spin correlations, W_L , resonance?

Constraining the Higgs



Beyond the Standard Model

- **A Cornucopia of Imaginations**

Higher mass bosons

- mass reach approaches 1 TeV

Leptoquarks

Compositeness (Drell-Yan, Jets)

- sensitivity in > 5 TeV region

- **Strong Coupling, Technicolor**

- **SUSY (The mainstream)**

- **Higgs (inc SM)**



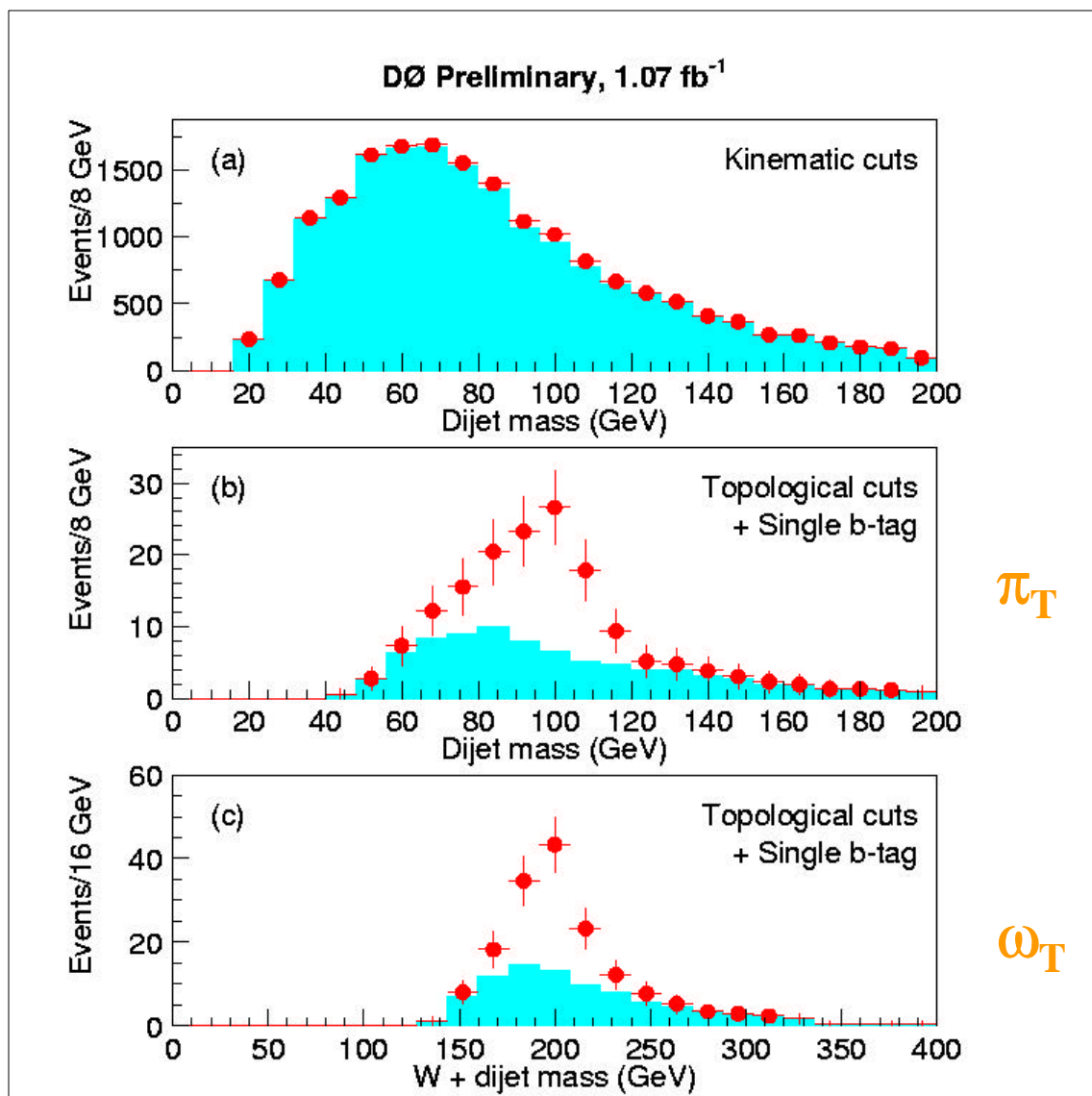
**“Run II”
Workshops
Experiments &
Theorists**

Technicolor

- Strong EW Symm. Breaking is possible
- Cross sections are substantial

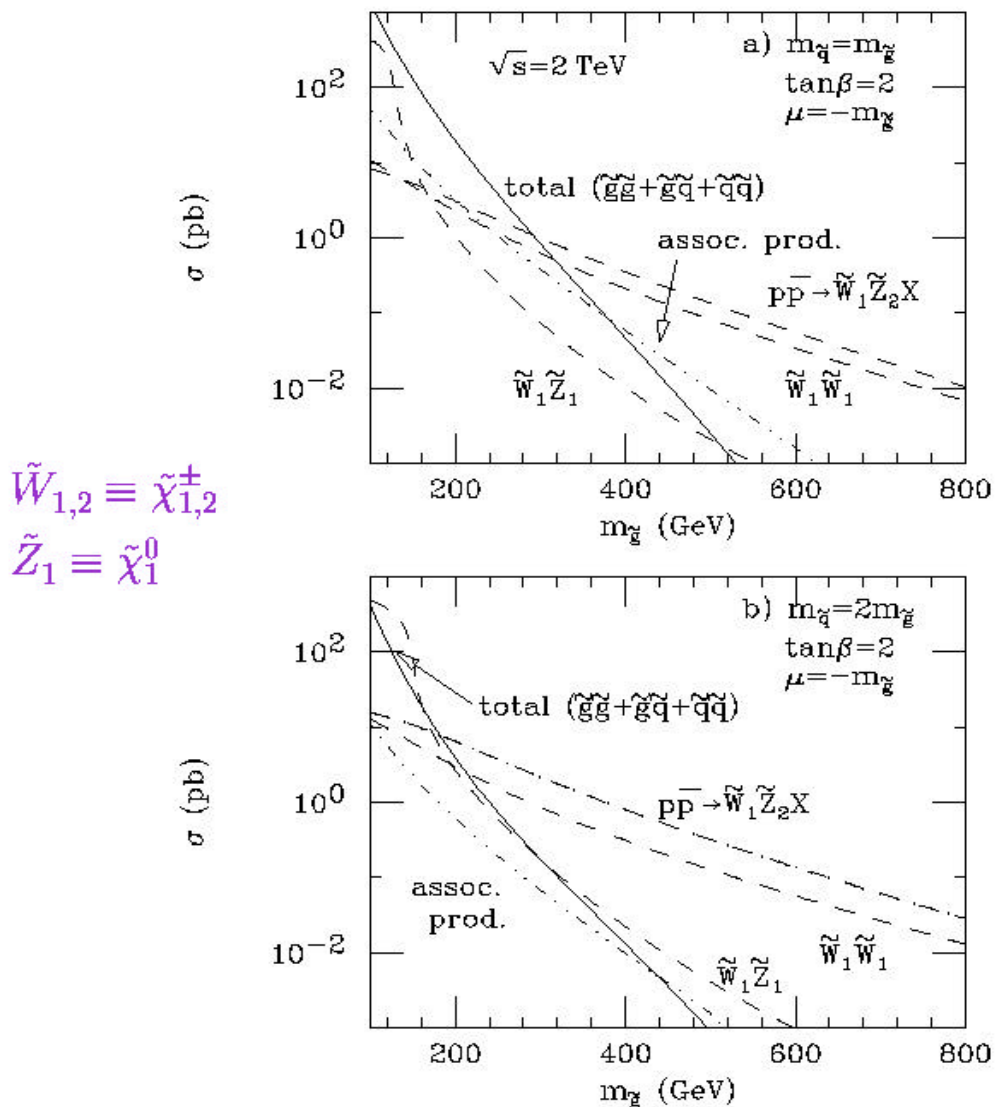
$$\text{eg } \omega_T \Rightarrow \pi_T + W$$

finds two new particles



SUSY

Sparticle Pair Production Cross Sections



- squark-gluino production cross sections drop rapidly w/ higher \tilde{g} masses where searches become kinematically limited
- $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are about 1/3 to 1/4 as massive as \tilde{q} and \tilde{g}
 \Rightarrow their cross sections become dominant for high \tilde{g} mass

SUSY

Summary: SUGRA and GMSB Working Groups

SUGRA: Maximum mass reach (5σ) in GeV/c^2

SUSY particle	Run I ($0.1\ fb^{-1}$)	Run II ($2\ fb^{-1}$)
$\tilde{\chi}_1^\pm$	70(*)	210
\tilde{g}	270(*)	390
$\tilde{t}_1(\rightarrow b\tilde{\chi}_1^\pm)$	-	170

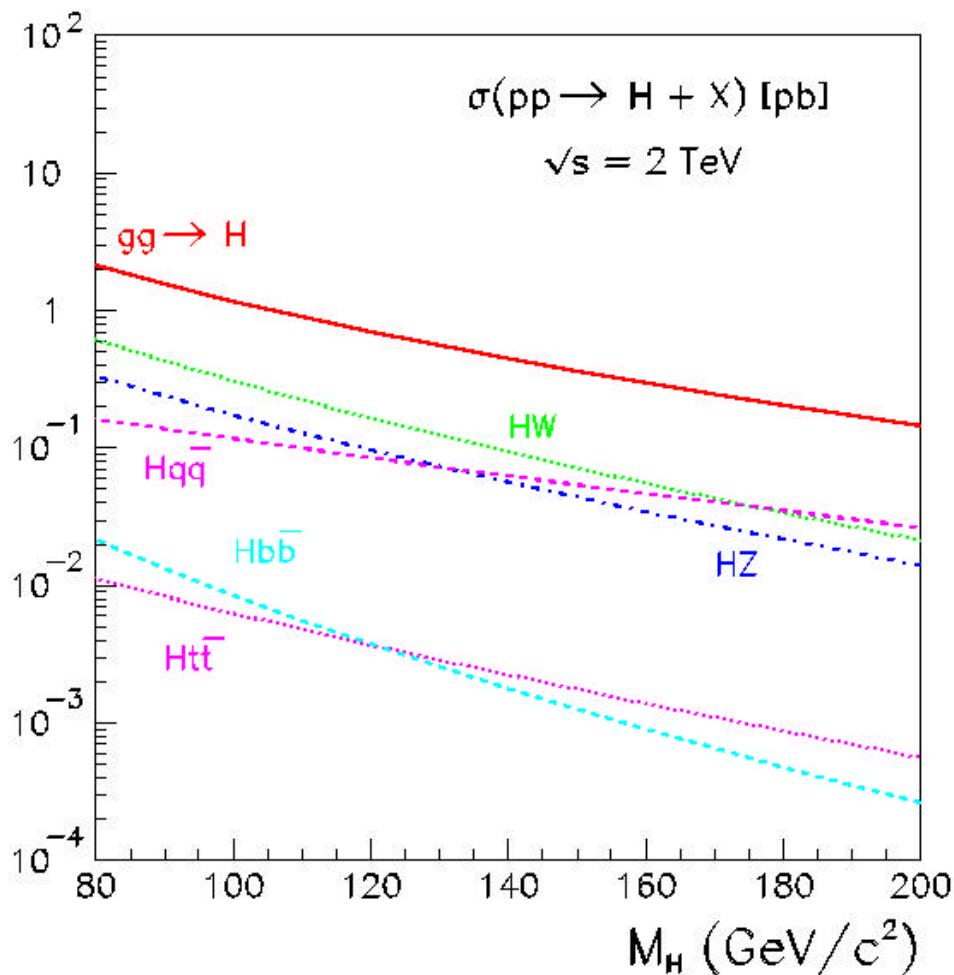
(*) indicates 95% CL limit

GMSB: Maximum mass reach (5σ) in GeV/c^2

SUSY particle	Run II ($2\ fb^{-1}$)
$\tilde{\chi}_1^\pm$	265
$\tilde{\tau}$	120

Higgs at the Tevatron

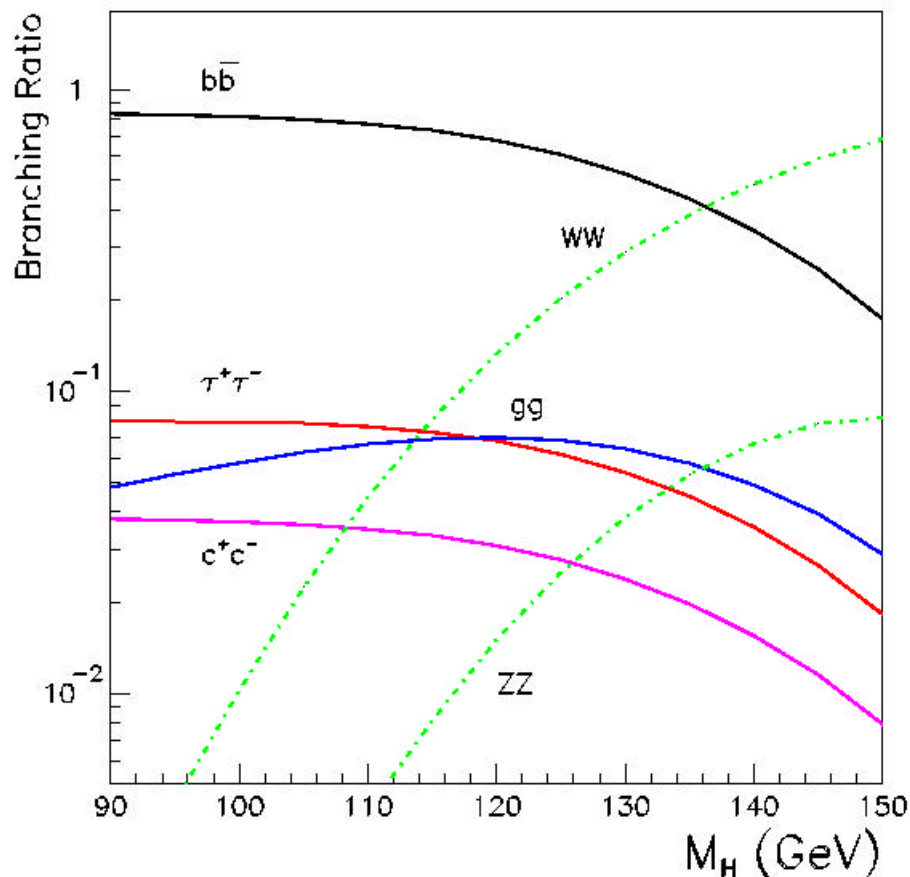
SM Higgs Production at the Tevatron



- $gg \rightarrow H, WH, ZH$ cross sections include full QCD corrections
- Higgs strahlung processes WH and ZH are accessible
- Higgs Yukawa couplings are enhanced in SUSY models

Higgs Branching Ratios

SM Higgs Production at the Tevatron



- dominant decay mode for $M_H < 130 \text{ GeV}/c^2$ is $H \rightarrow b\bar{b}$

WH/ZH final states: $q\bar{q}b\bar{b}$, $l\nu b\bar{b}$ and $\nu\bar{\nu}b\bar{b}$, $l^+l^-b\bar{b}$

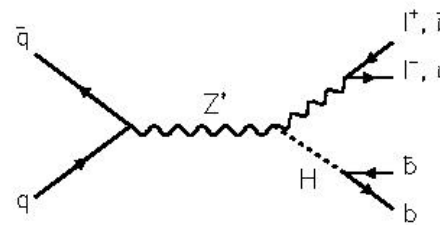
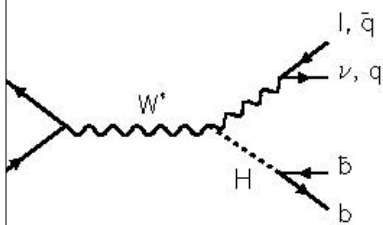
- for $M_H > 130 \text{ GeV}/c^2$, $H \rightarrow WW$ dominates

WW final states with > 2 leptons: $l^\pm l^\pm jj$, $l^+l^- \nu\bar{\nu}$

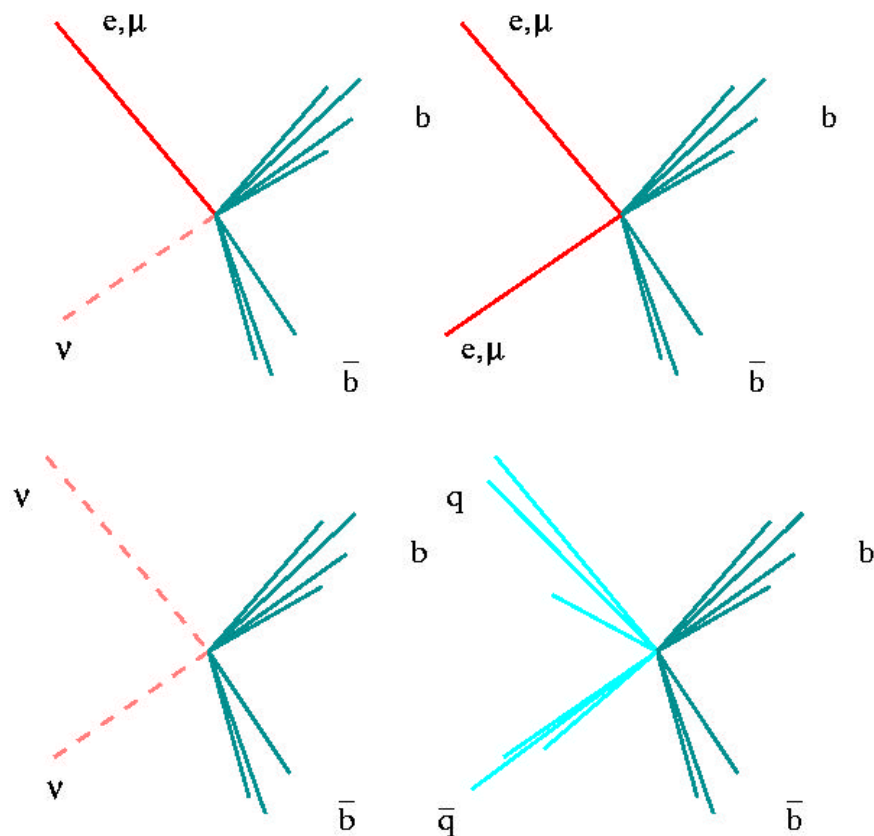
Higgs at the Tevatron

SM Higgs Searches, $M_H < 130 \text{ GeV}/c^2$

Higgs Strahlung off W/Z Bosons



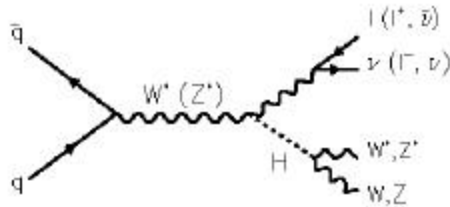
Topologies:



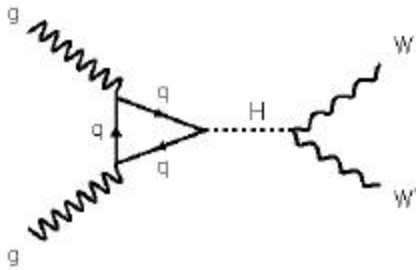
Higgs at the Tevatron

SM Higgs, $M_H > 130 \text{ GeV}$

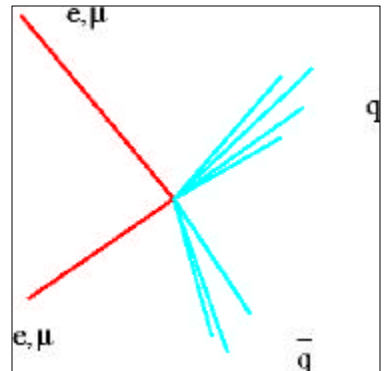
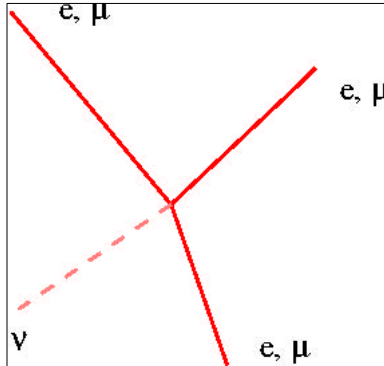
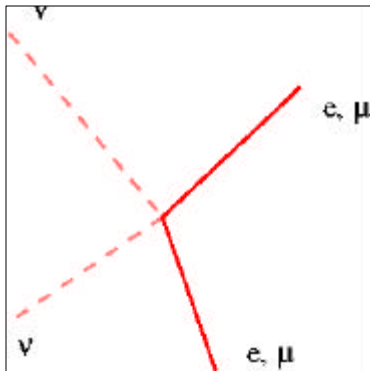
Higgs Strahlung off W/Z Bosons



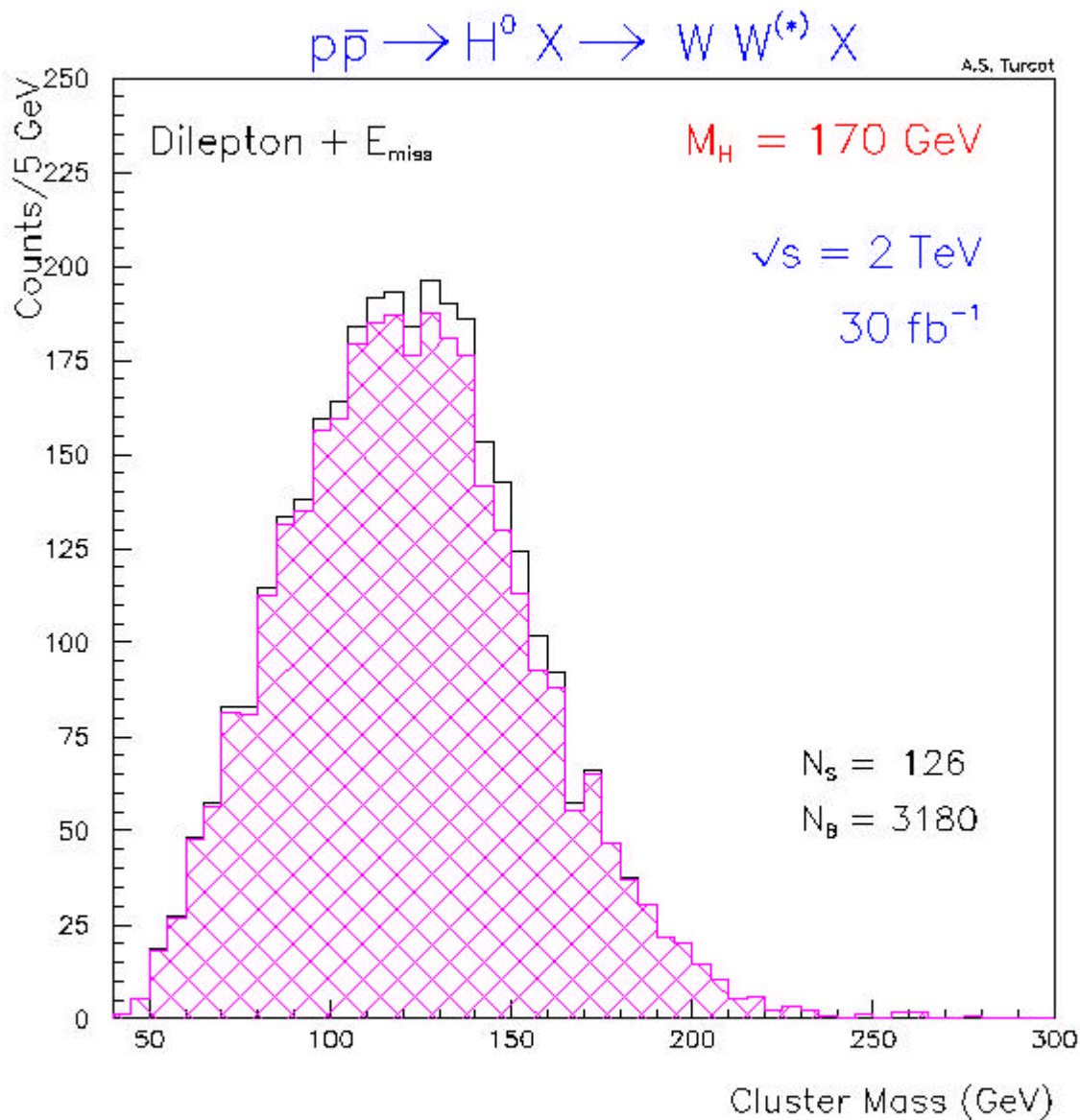
Gluon-Gluon Fusion $gg \Rightarrow H$



Topologies



- Before “Turning the Screw”

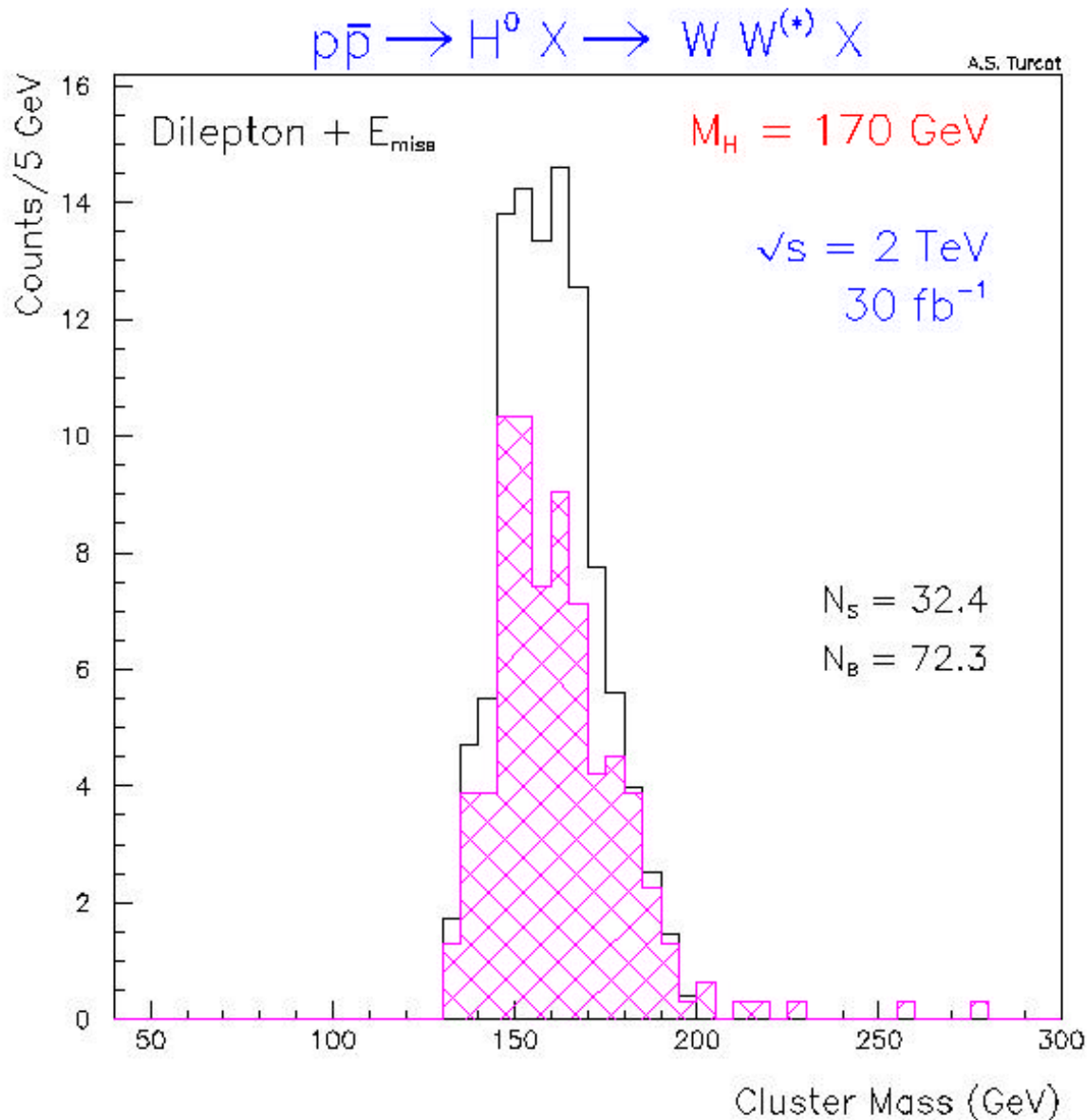


- Normalization of the Background

$10 \text{ fb}^{-1} \Rightarrow 3.1\% \text{ statistical error}$

Higgs contamination: $S/B \sim 3 - 5\%$

- After “Turning the Screw”



- WW background reduced by a factor of 40! ($M_H = 170$)

Higgs Sensitivities

Overview of SM Higgs Channel Sensitivities

channel	rate	Higgs mass (GeV/c ²)				
		90	100	110	120	130
$\nu\bar{\nu}b\bar{b}$	S	2.5	2.2	1.9	1.2	0.6
	B	10.0	9.3	8.0	6.5	4.8
	S/\sqrt{B}	0.8	0.7	0.7	0.5	0.3
$\ell\nu b\bar{b}$	S	8.4	6.6	5.0	3.7	2.2
	B	48	52	48	49	42
	S/\sqrt{B}	1.2	0.9	0.7	0.5	0.3
$l^{\pm}b\bar{b}$	S	1.0	0.9	0.8	0.5	0.3
	B	3.6	3.1	2.5	1.8	1.1
	S/\sqrt{B}	0.5	0.5	0.5	0.4	0.3
$q\bar{q}b\bar{b}$	S	8.1	5.6	3.5	2.5	1.3
	B	6800	3600	2800	2300	2000
	S/\sqrt{B}	0.10	0.09	0.07	0.05	0.03

Expected #
of events and
sensitivity in
 $\mathcal{L} = 1 \text{ fb}^{-1}$

bbbar

• Run II
acceptance

• 30% improved
 $M_{b\bar{b}}$ resolution

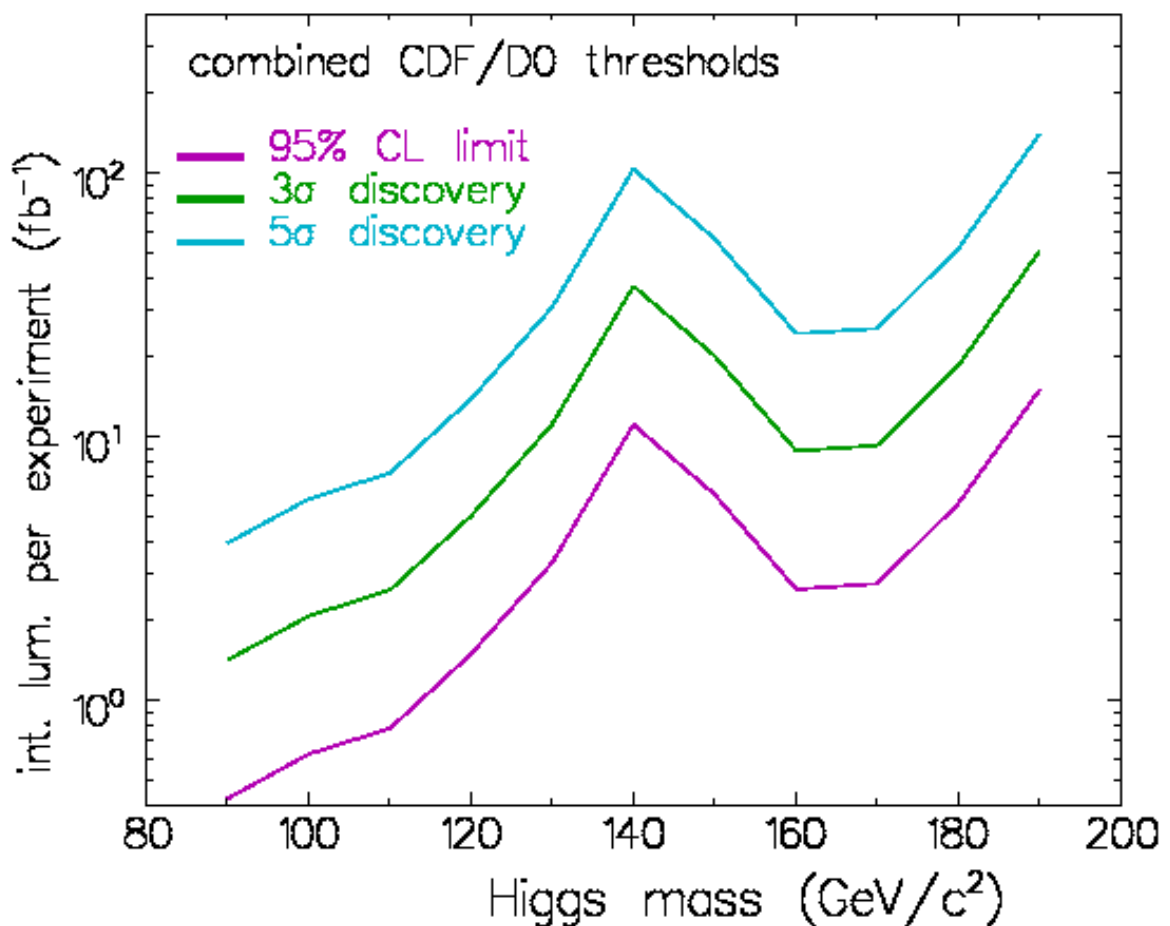
channel	rate	Higgs mass (GeV/c ²)							
		120	130	140	150	160	170	180	
$\ell^{\pm}\ell^{\pm}\ell^{\mp}$	S	0.04	0.08	0.11	0.12	0.15	0.10	0.09	
	B	0.73	0.73	0.73	0.73	0.73	0.73	0.73	
	S/\sqrt{B}	0.05	0.09	0.13	0.14	0.18	0.12	0.11	
$\ell^+\ell^-\nu\bar{\nu}$	S	-	-	2.6	2.8	1.5	1.1	1.0	
	B	-	-	44	30	4.4	2.4	3.8	
	S/\sqrt{B}			0.39	0.51	0.71	0.71	1.9	
$\ell^{\pm}\ell^{\pm}jj$	S	0.10	0.20	0.34	0.53	0.45	0.38	0.29	
	B	0.85	0.85	0.85	0.85	0.85	0.85	0.85	
	S/\sqrt{B}	0.11	0.22	0.37	0.57	0.49	0.41	0.31	

II

Standard Model Higgs

Combined channel thresholds

- Gaussian approximation in combination
- 30% better $m_{b\bar{b}}$ resolution than Run 1
- Run 2 acceptance $\times 1.3$ NN improvement
- 10% systematic error on background
- all except $\ell^\pm\ell^\pm jj$

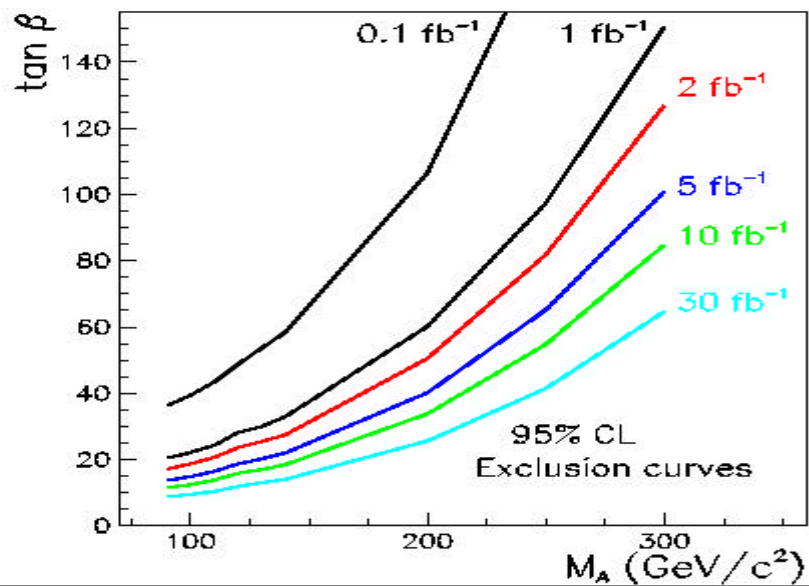
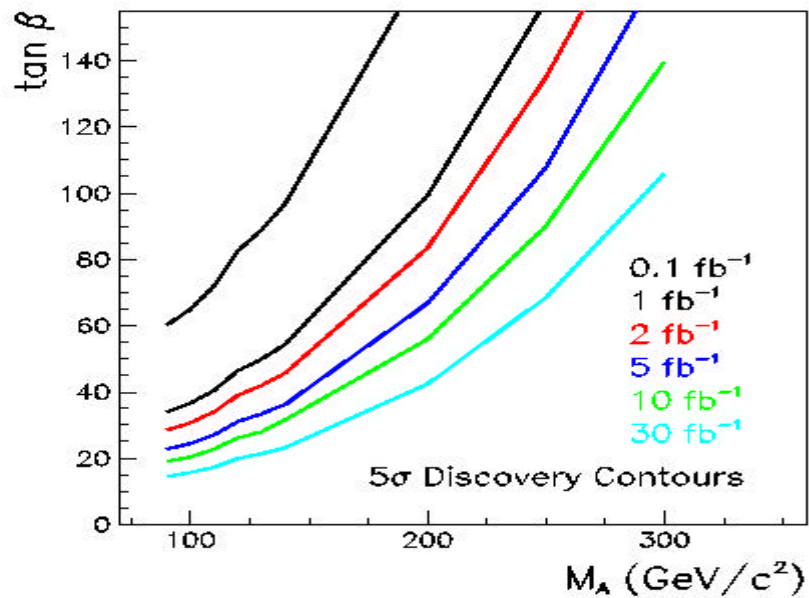


Revelation from November Run II Workshop!

SUSY Higgs

Limits in the M_A and $\tan \beta$ plane

$$p\bar{p} \rightarrow b\bar{b} + (h, A, H) \rightarrow b\bar{b}b\bar{b}$$



The MI Physics Program

- **Main Injector - Commissioning going well**
- **Collider - CDF, D0 - Start 2000**
 - **Electroweak, Top, $\sin 2\beta$, B_s**
 - **SUSY, Technicolor**
 - **Higgs Discovery?**
- **Neutrinos - NuMI “Baselined”**
 - **Nail the Oscillations**
- **CP Violation, CPT violation in Kaons**
- R&D Projects
- **BTeV, -R&D Project**
- **(FT QCD - excellent potential)**
- **Broad Attack on Physics Frontiers**